LIDS

Toward the joint design of electronic and optical layer protection

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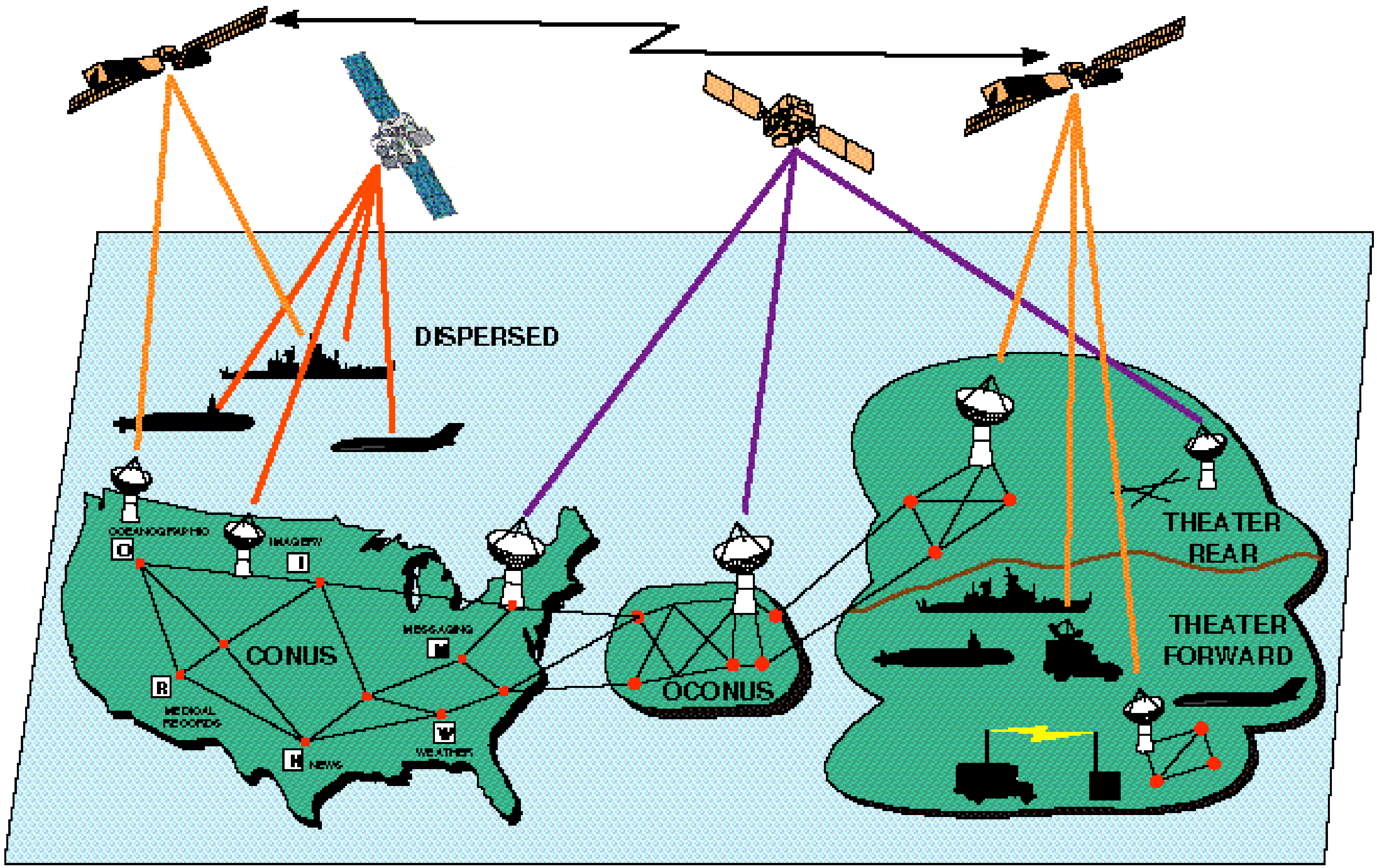
COMMUNICATIONS CONNECTIVITIES



= SATCOM/DISN TELEPORT

CHALLENGES:

- SEAMLESS CONNECTIVITY
- MULTI-MEDIA (FIBER,SATCOM,WIRELESS)
- HETEROGENEOUS PROTOCOLS

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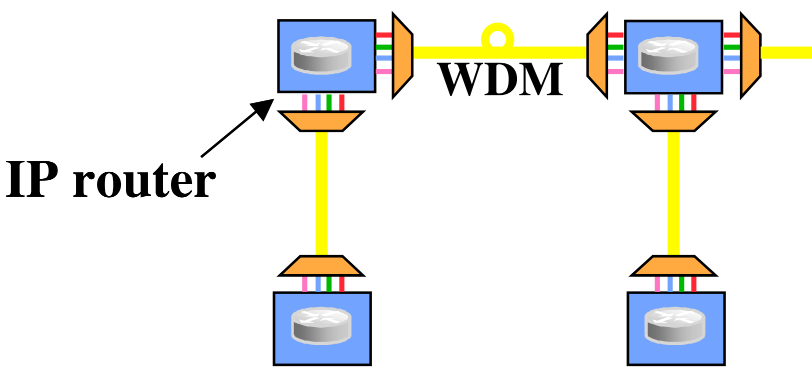
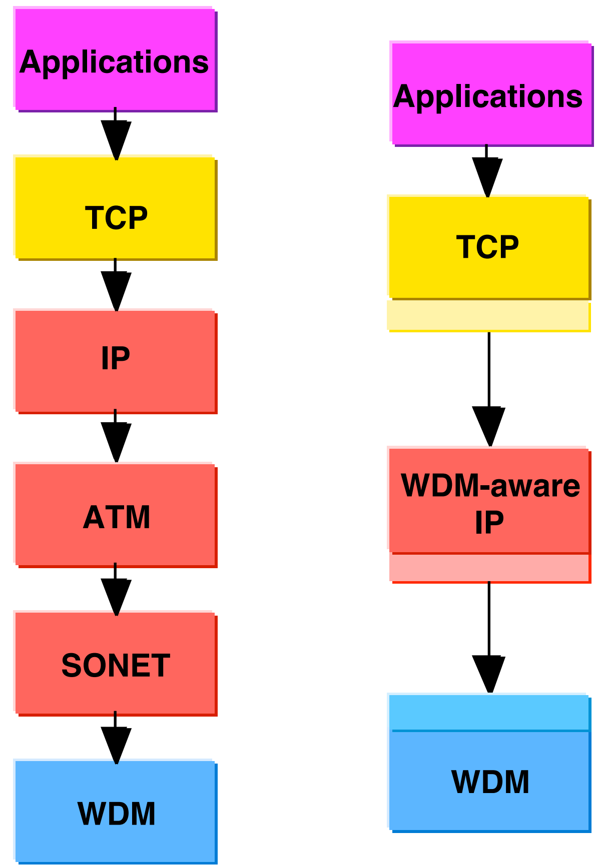
IP-over-WDM

- Networks use many layers
  - Inefficient, expensive
- Goal: reduced protocol stack
  - Eliminate electronic layers
  - Preserve functionality
- Joint design of electronic and optical layers
  - Medium access protocol
  - Topology reconfiguration
  - Efficient multiplexing (grooming)
  - Joint electronic/optical protection





Outline

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- ***Survivable routing of logical topologies:*** **How to embed the logical topology on a physical topology so that the logical topology can withstand physical link failures**

- ***Physical topology design:*** **How to design the physical topology so that it can be used to embed rings in a survivable manner**

- ***Path protection with failure localization:*** **What are the benefits of failure localization for path protection**

Physical Topology vs Logical Topology

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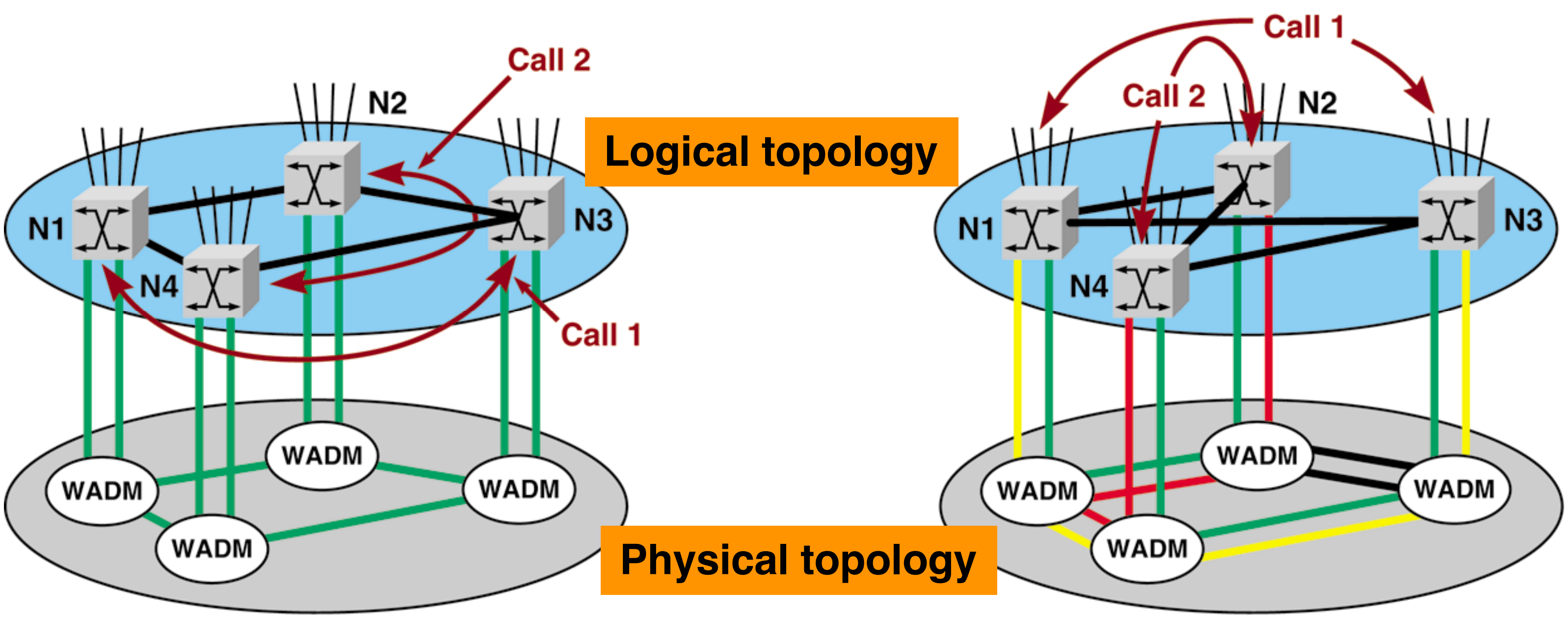
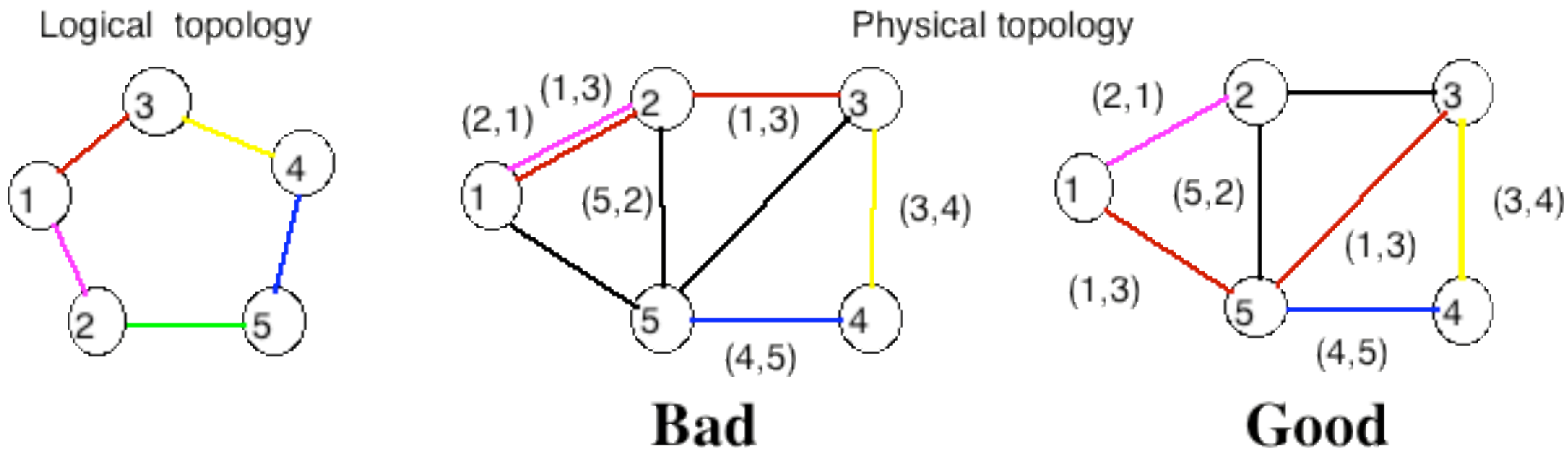
- **Physical Topology**
  - Optical layer topology
  - Optical nodes (switches) connected by fiber links
- **Logical Topology**
  - Electronic layer topology; e.g., routers connected by *lightpaths*
    - Lightpaths must be routed on the physical topology
    - Lightpaths are established by tuning transceivers and switches



Routing the logical topology on a physical topology



- How do we route the logical topology on the physical topology so that we can keep the logical topology protected ?
  - Logical connections are lightpaths that can be routed in many ways on the physical topology
  - Some lightpaths may share a physical link in which case the failure of that physical link would cause the failure of multiple logical links
    - For rings (e.g., SONET) this would leave the network disconnected
  - Need to embed the logical topology onto the physical topology to maintain the protection capability of the logical topology

Application

- **Protection provided at the electronic layer**
  - **E.g., SONET, ATM, IP**
  - **Physical layer protection is redundant**
- **However, must make sure that the protection provided at the electronic layer is maintained in the event of a physical link cut**
- **Simple solution: Route all logical (electronic) links on disjoint physical routes**
  - **E.g., physical and electronic topologies look the same**
  - **Approach may be wasteful of resources**
  - **Disjoint paths may not be available**

Alternative approach

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- Route the lightpaths that constitute the electronic topology in such a way that the protection capability is maintained

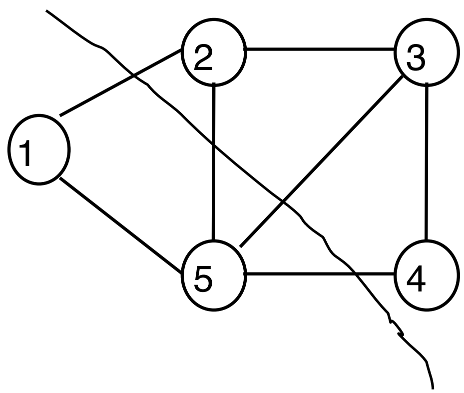
- Examples:
  - Make sure logical topology remains connected in the event of a physical link failure
  - For SONET rings, make sure alternative route exists in the event of a physical link failure (same as topology remains connected)

- Our focus: Route the lightpaths of the logical topology so that it remains connected in the event of any single physical link failure

Eytan Modiano and Aradhana Narula-Tam, "Survivable lightpath routing: A new approach to the design of WDM-based networks," IEEE Journal of Selected Areas in Communication, May 2002.

Cut-set formulation

- **Consider a graph (N, E)**
  - **A *cut* is a partition of the set of nodes N into subsets S and N-S**
  - **The *cut-set* CS(S,N-S) is the set of edges in the graph that connect a node in N to a node in N-S**
  - **The size of the cut-set is the number of edges in the cut-set**



S = {1,5}, N-S = {2,3,4}

CS(S,N-S) = {(1,2), (5,2),(5,3),(5,4)}

<u>Menger's Theorem</u>: A logical topology is 2-connected if for every cut (S,S-N)

$$|CS(S,N\text{-}S)| \geq 2$$

Condition for survivable routing

Theorem 1: A routing is survivable *if and only if* for every cut-set $CS(S,N_L-S)$ of the logical topology the following holds:

Let E(s,t) be the set of physical links used by logical link (s,t). Then, for every cut-set $CS(S,N_L-S)$,

$$\bigcap_{(s,t)\in CS(S,N_L-S)} E(s,t) = \varnothing$$

- The above condition requires that no single physical link is shared by all logical links belonging to a cut-set of the logical topology
  - not all of the logical links belonging to a cut-set can be routed on the same physical link
- This condition must hold for all cut-sets of the logical topology

ILP formulation of survivable routing problem

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Minimize $\sum_{\substack{(i,j)\in E \\ (s,t)\in E_L}} f_{ij}^{st}$ **Subject to:**

A) Connectivity constraints:

$$\sum_{j\ s.t.(i,j)\in E} f_{ij}^{st} - \sum_{j\ s.t.(j,i)\in E} f_{ji}^{st} = \begin{cases} 1 & if \quad s=i \\ -1 & if \quad t=i \\ 0 & otherwise \end{cases}$$

B) Survivability constraints:

$$\begin{matrix}\forall (i,j)\in E \\ \forall S \subset N_L\end{matrix}, \quad \sum_{(s,t)\in CS(S,N_L-S)} f_{ij}^{st} + f_{ji}^{st} < \left|CS(S,N_L - S)\right|$$

C) Capacity constraints:

$$\forall (i,j)\in E, \quad \sum_{(s,t)\in E_L} f_{ij}^{st} \le W$$

D) Integer flow constraints:

$$f_{ij}^{st} \in \{0,1\}$$

Solving the ILP

- Difficult for large networks due to the large number of constraints
  - Exponential number of cut-set constraints
- Solution for ILP can be found using branch and bound and other heuristic techniques
- Alternatively relaxations of the ILP can be found that remove some of the constraints
  - LP relaxation removes the integer constraints, but unfortunately solution becomes non-integer => can't determine the routings
  - Can relax some of the less critical survivability constraints
    - Start with only a subset of the cut-set constraints, if survivable solution is found then done; otherwise add more cut-set constraints until survivable solution is found

ILP relaxations

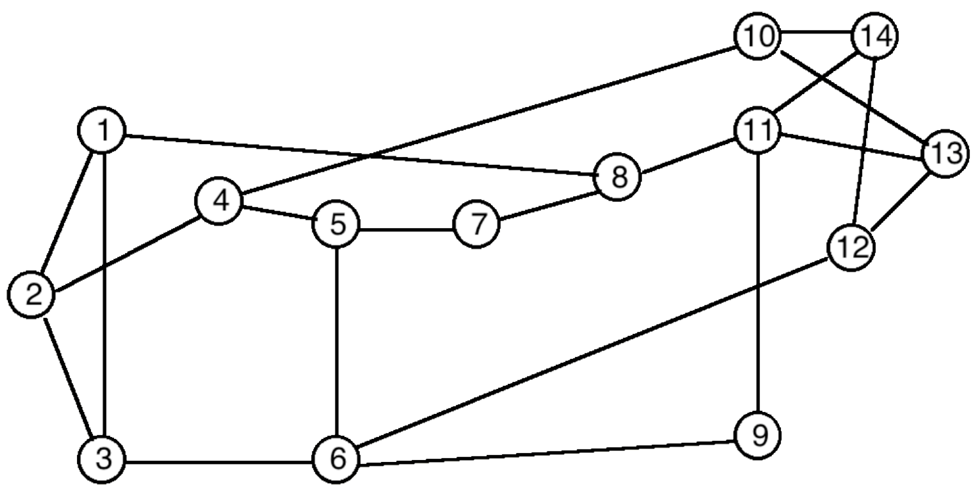
- **Single node cuts relaxation: Consider only those cuts that separate a single node from the rest of the network**
  - **Only N such cut-sets**
  - **Single node cuts are often the smallest and hence the most vulnerable**
  - **When network is densely connected most cuts contain many links and are not as vulnerable**

- **Small cut-sets relaxation: Consider only those cut-sets whose size is less than a certain size (e.g., the degree of the network, degree + 1, etc.)**
  - **This relaxation includes all the single node cuts, but some other small cuts as well**
  - **Appropriate for less densely connected networks**

NSF Network experiments

- **Logical topologies**
  - Randomly generated logical topologies of degrees 3, 4, 5
    100 randomly generated topologies of each size

- **Physical topology**
  - NSF NET (14 nodes, 21 links)



Results: Degree 3 logical topologies

	Logical Top's	Unprotected solution	Ave. links	Ave. λ∗links
ILP	100	0	19.76	46.07
Short Path	100	86	19.31	45.25
Relax - 1	100	10	19.78	46.03
Relax - 2	100	0	19.78	46.07

Results: Degree 4 logical topologies

	Logical Top's	Unprotected solution	Ave. links	Ave. λ*links
ILP	100	0	20.30	60.64
Short Path	100	38	20.17	60.47
Relax - 1	100	0	20.30	60.64
Relax - 2	100	0	20.30	60.64

Results: Degree 5 logical topologies

	Logical Top's	Unprotected solution	Ave. links	Ave. λ*links
ILP	100	0	20.56	75.40
Short Path	100	27	20.48	75.31
Relax - 1	100	0	20.56	75.40
Relax - 2	100	0	20.56	75.40

Run times of algorithms

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	ILP	Relaxation - 1	Relaxation - 2
Degree - 3	8.3 s	1.3 s	1.3 s
Degree - 4	2 min. 53 sec.	1.5 s	1.5 s
Degree - 5	19 min. 17 sec.	2.0 s	2.0 s

Sun Sparc Ultra 10 computer

Ring Logical topologies

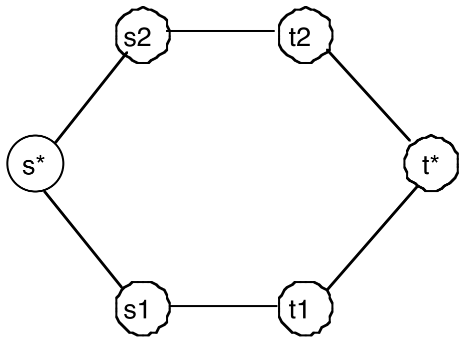
- Widely used topology (e.g., SONET rings)
- Ring topology yields simple solutions
  - It can be easily shown that every cut of a bi-directional ring contains exactly two links
  - It can also be shown that every pair of links shares a cut
- Corollary: A bi-directional logical ring is survivable if and only if no two logical links share the same physical link
  - The proof is a direct result of Theorem 1
  - Cut-set constraints can be replaced by a simple capacity constraint on the links

$$\forall (i, j) \in L, \quad \sum_{(s,t) \in E_L} f_{ij}^{st} + \sum_{(s,t) \in E_L} f_{ji}^{st} \leq 1$$

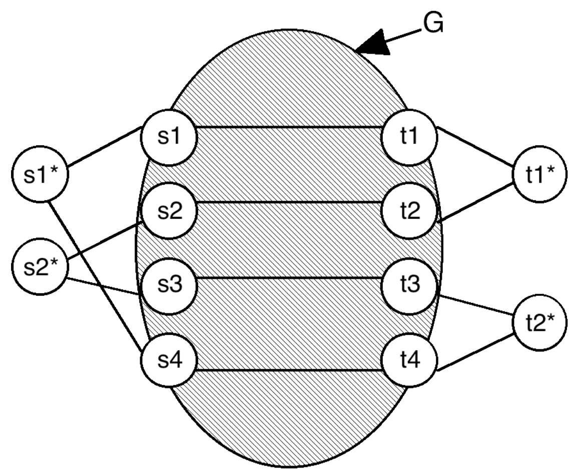
NP-completeness

Theorem 2: The survivable routing problem is NP-complete

Proof: Mapping of ring survivable routing to k edge disjoint paths in undirected graphs



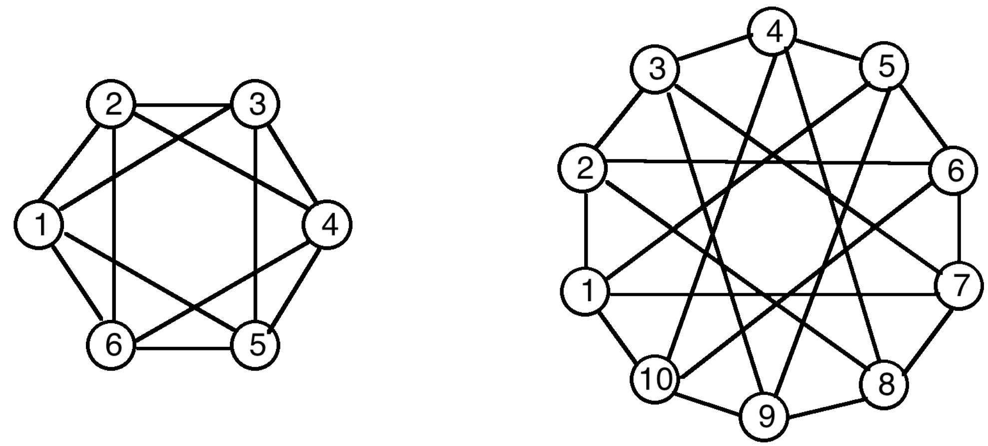
Two-edge disjoint paths



Four-edge disjoint paths

Ring experiments

- **Physical topologies:**



6 nodes 10 nodes

- **Logical topologies:**
  - **All possible 6 node logical rings (120 possible) on 6 node physical**
  - **All possible 6,7,8,9, and 10 node rings on 10 node physical**

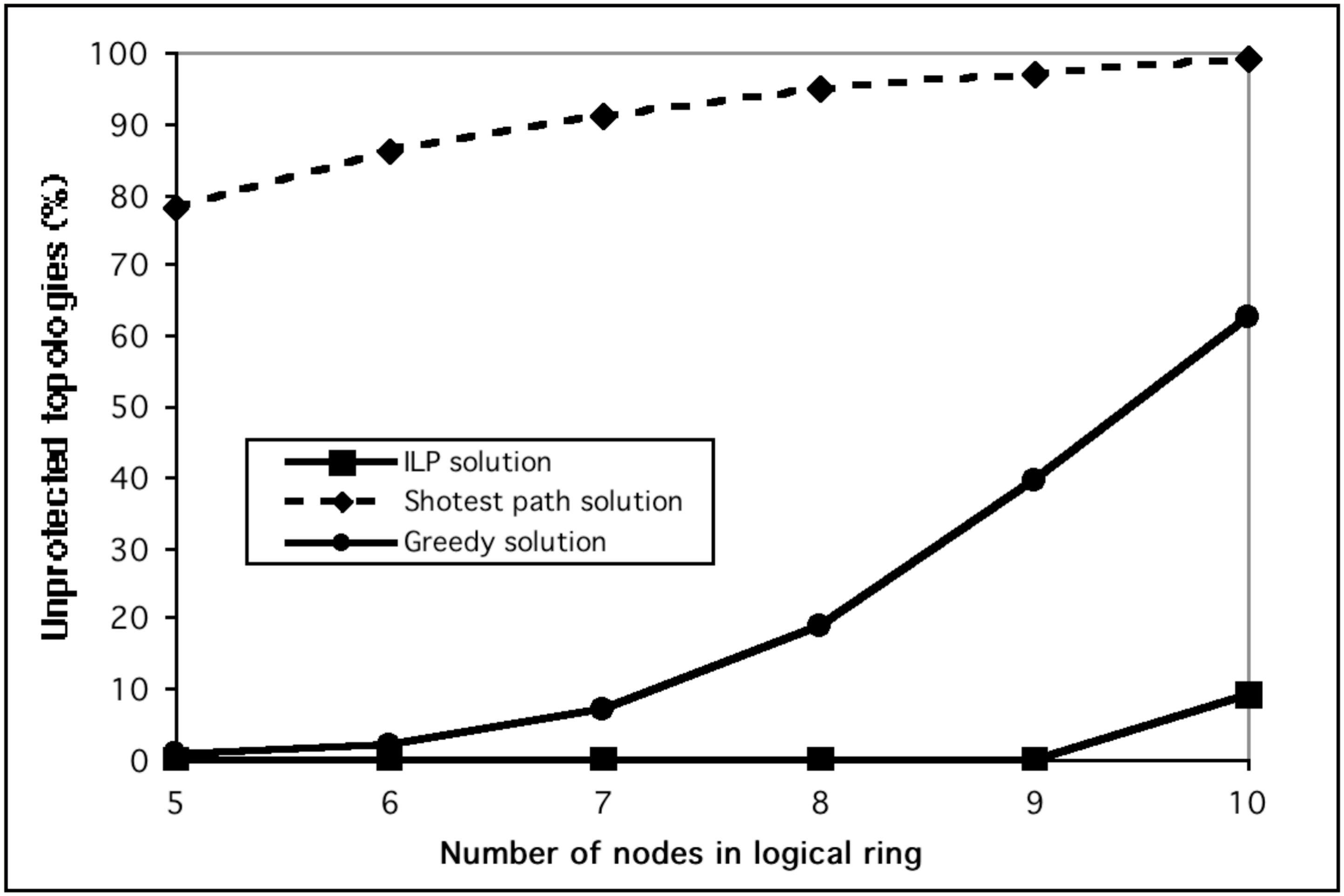
Routing Algorithms

- **Survivable routing - ILP solution**
  - Guarantees survivable routing whenever one exists

- **Shortest path routing**
  - Find the shortest path for every lightpath regardless of survivability

- **Greedy routing**
  - Route lightpaths sequentially using shortest path
  - Whenever a physical link is used by a lightpath, it is removed so that it cannot be used by any other lightpath
    - Takes advantage of the fact that for ring logical topologies no two lightpaths can share a physical link

Ring results



Ring results, cont.

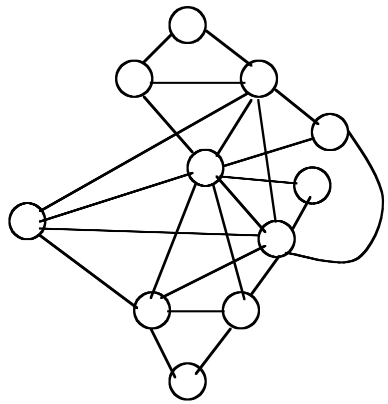
	Logical Top's	No protected solution	Ave. links	Ave. λ*links
6 node-ILP	120	0	7.4	7.4
6 node - SP	120	64 (53%)	6.4	7.2
6 node - GR	120	0	8.1	8.1
10 node-ILP	362880	33760 (9%)	17.8	17.8
10 node - SP	362880	358952 (99%)	11.8	15.5
10 node - GR	362880	221312 (61%)	18.4	N/A

Outline

- **Survivable routing of logical topologies**
- ***Physical topology design***
- **Path Protection with failure localization**

Physical Topology Design: Embedding Survivable Rings

- N node Network: Embed all permutations of rings of size K<= N
  - There are $\binom{N}{K}(K-1)!$ rings of size K
- Typical physical topologies are not conducive to embedding rings in survivable manner



- 11 Node NJ LATA
- Supports only 56% of all 9 node rings

- Goal: Design physical topologies that can support survivable logical rings
  - Use minimum number of physical links

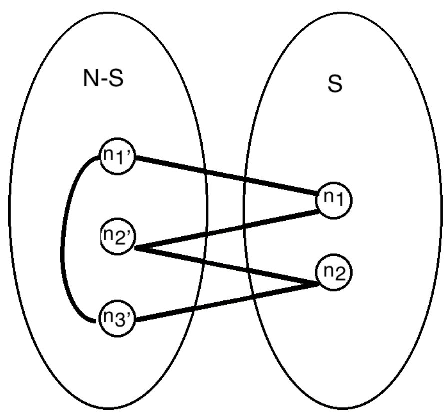
A. Narula-Tam, E. Modiano, A. Brzezinski, "Physical Topology Design for Survivable Routing of Logical Rings in WDM-Based Networks," IEEE JSAC, October, 2004.

Necessary conditions for physical topology

- **Under what condition can one embed any ring logical topology on a given physical topology**
  - **Want to design a physical topology that can support all possible ring logical topologies**
    - **Service provider that receive requests for ring topologies and wants to make sure that he can support all requests in a survivable manner**

Theorem 3: **In order for a physical topology to support any possible ring logical topology, any cut of the physical topology (S, N-S),**

$$|CS_P(S, N-S)| \geq 2 \min(|S|, |N-S|)$$



Necessary conditions for physical topology

- **Theorem 3 provides insights on physical topology design**
  - **E.g., all neighbors of degree 2 nodes must have degree ≥ 4**

- ***Theorem 4:*** **The number of links that an N node physical topology must have in order to guarantee survivable routing of K node logical rings is given by:**

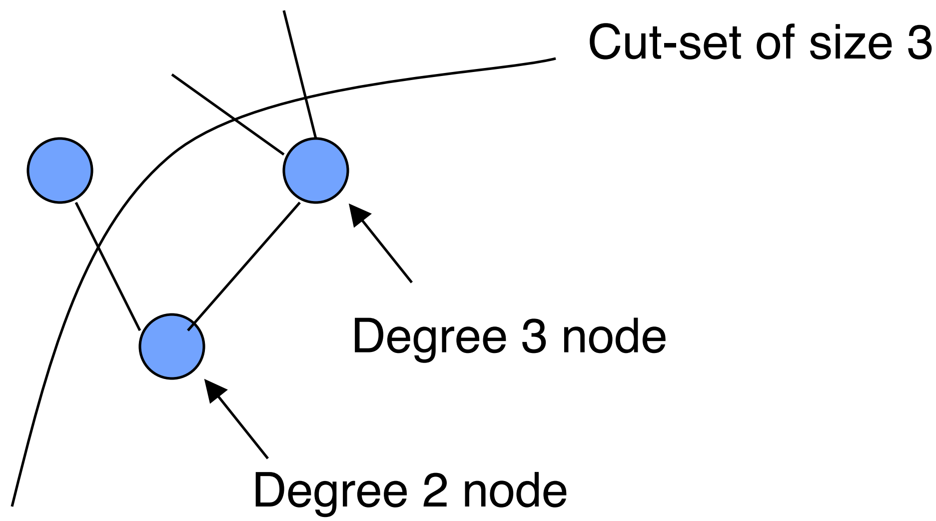
Logical Ring Size	*Physical link requirement*
$K = 4$	$4N/3$
$K = 6$	$3N/2$
$K = 8$	$1.6N$
$K = N - 1$	$2N - 3$

- **Proof: by repeated application of Theorem 3**

Proof: K=4 case

***Lemma*: Any node of degree 2 must have physical links to nodes of degree 4 or higher.**

***Proof:* Suppose a node of degree 2 has a physical link to a node of degree 3, then the cut-set consisting of the degree 2 node and its degree 3 neighbor contains only 3 links. However, since the cut-set contains two nodes, *Theorem 3* requires a minimum of 4 cut-set links.**



Proof of Theorem 4 (K = 4 case)

Let d_i be the number of nodes with degree i in the physical topology. Then the number of links in the physical topology is

$$L = \sum_{i=2}^{N-1} \frac{id_i}{2} = d_2 + \frac{3d_3}{2} + \sum_{i=4}^{N-1} \frac{id_i}{2}$$

From lemma 1: $d_2 \le \sum_{i=4}^{N-1} \frac{i}{2} d_i \longrightarrow L \ge 2d_2 + \frac{3}{2} d_3$ (1)

Also, since nodes of degree i, add a minimum of i/2 physical links we get:

$$L \ge \frac{2d_2 + 3d_3 + 4(N - d_2 - d_3)}{2} = 2N - d_2 - \frac{d_3}{2} \quad (2)$$

(1) & (2) => $L \ge \max(2d_2 + \frac{3}{2} d_3, 2N - d_2 - \frac{d_3}{2})$

Proof, cont.

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$$L \geq \max(2d_2 + \frac{3}{2}d_3, 2N - d_2 - \frac{d_3}{2})$$

Minimum occurs when $$2d_2 + \frac{3}{2}d_3 = 2N - d_2 - \frac{d_3}{2}$$

$$\longrightarrow \quad d_2 = \frac{2N - 2d_3}{3}$$

$$\longrightarrow \quad L \geq \frac{4N}{3} + \frac{d_3}{6} \geq \frac{4N}{3}$$

Similar arguments for proving the K=6 and K=8 cases

K= N-2 case: Show that we can find an N-2 node logical topology that requires at least 2(N-2) links

Integer Linear Program (ILP) Problem Formulation

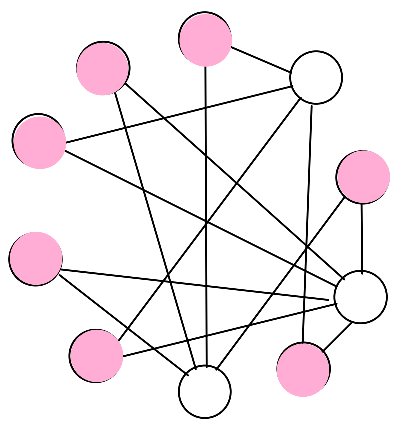
- Embed batch of R random rings of size K
- Start with a fully connected physical topology with cost of each physical link = 1
  - Minimize number of physical links used to embed all R rings
- ILP results
  - Solvable for small instances
  - Yields insights on properties of appropriate physical topologies

    E.g., solutions tend to have a "multi-hub" architecture

N=10

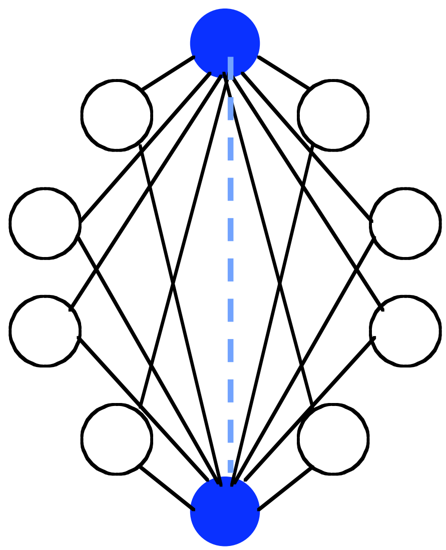
R=20

K=6



Physical Topologies for Embedding Logical Rings

- **Dual hub architecture**



- **N nodes, 2(N-2) bi-directional links**
- **Supports all logical rings of size ≤ N-2**
- **Uses minimal number of physical links**
- **With additional link can support all logical rings of size ≤ N-1**

Physical Topology for Embedding Rings of Size N

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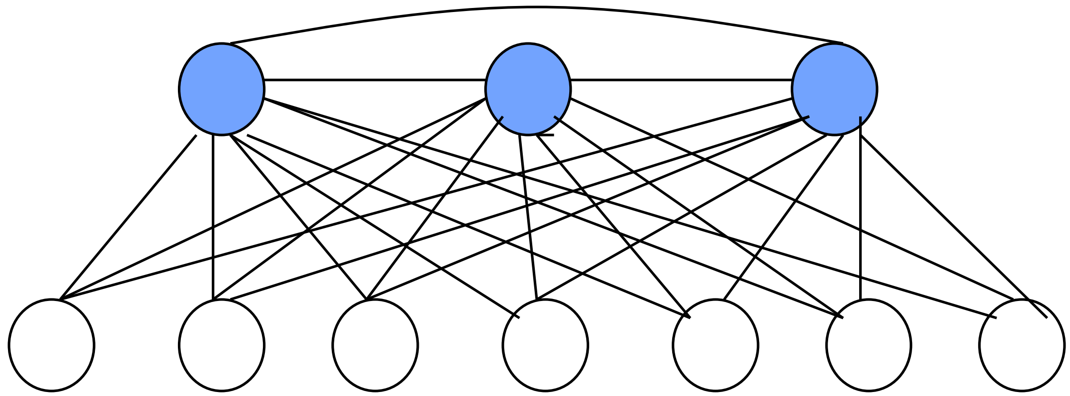

- Embedding rings of size N is considerably more difficult
- Three hub architecture
- Requires 3N–6 physical links
- Recall, rings of size N-1 required 2N-3 physical links
- Can we do better?

Outline

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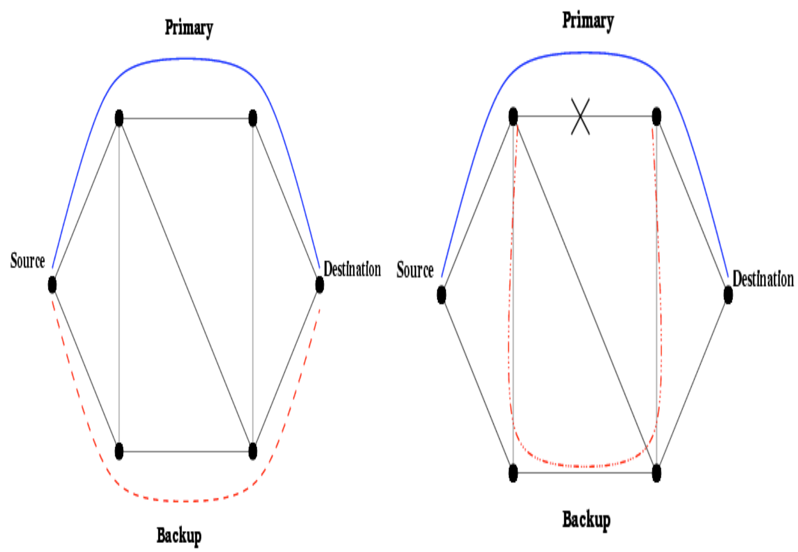
- **Survivable routing of logical topologies**
- **Physical topology design**
- ***Path Protection with failure localization***

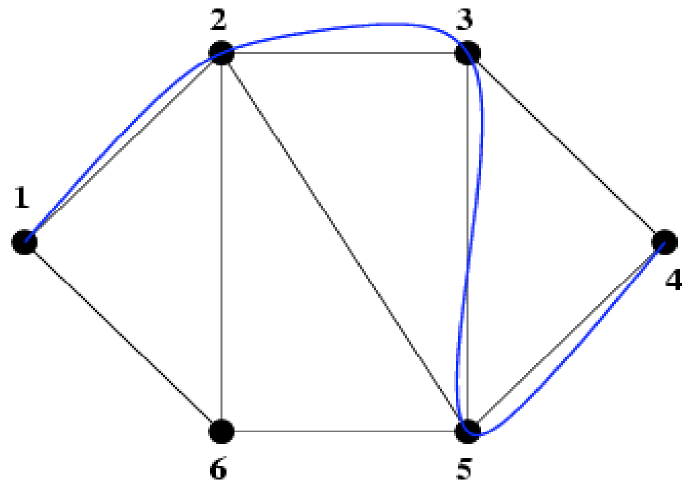
Path Protection and Link Protection



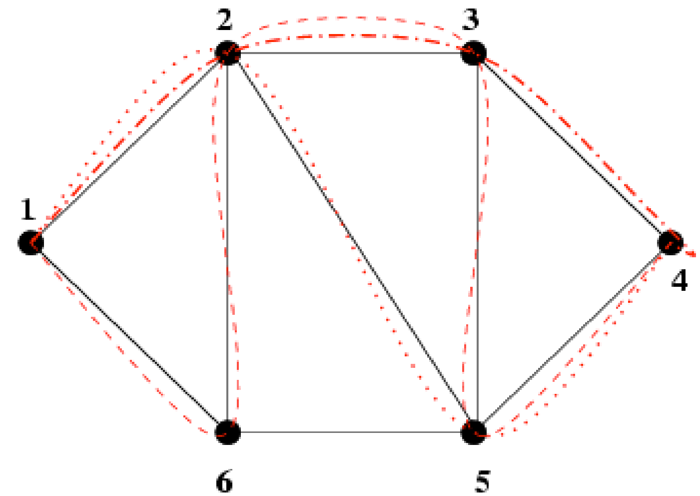
Protection Schemes	PP	LP
Major Feature	Link-Disjoint	Localization
Resource Efficiency	High	Low

Path Protection with Failure Localization (PPFL)

- **System specifies an end-to-end backup path to each link along the primary path**



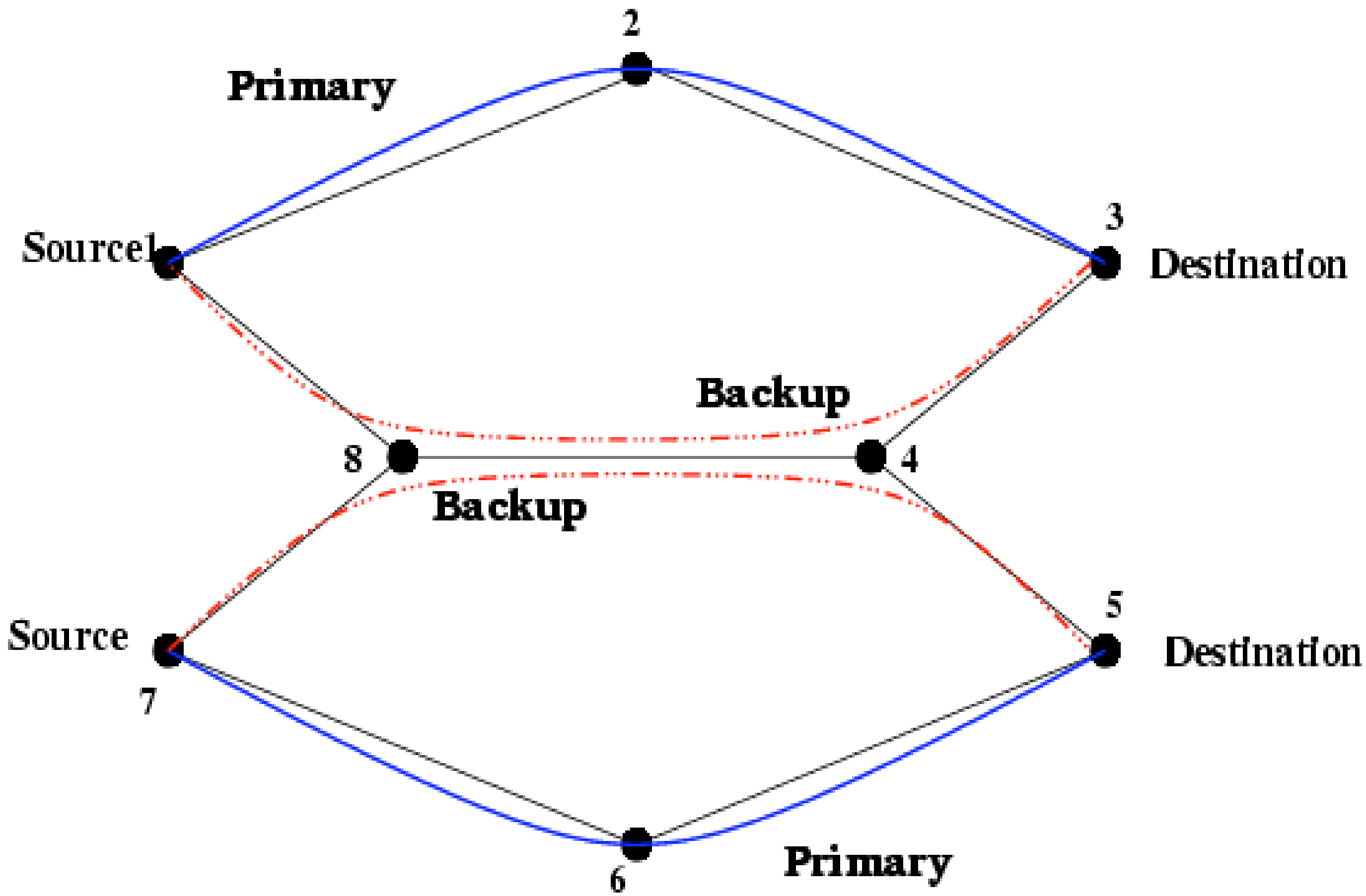
Primary Path



Backup Paths

Link on Primary Path (1-2-3-5-4)	Corresponding Protection Path
(1,2)	1-6-2-3-5-4
(2,3)	1-2-5-4
(3,5)	1-2-5-4
(5,4)	1-2-3-4

Protection Sharing



PPFL offers greater opportunity for resource sharing

Traffic Model

- Batch call arrival
  - Typical of a static routing and wavelength assignment problem
  - Usually done for the purpose of logical topology design
  - Requires solving for primary and backup paths for all sessions simultaneously

- Dynamic (random) call arrivals
  - Call-by-call model
    - Poisson call arrivals
    - Exponential holding times
  - Resources are allocated on a call by call basis, depending on network state information

Our focus: Dynamic call-by-call model

Implementation: Greedy and Heuristic Approach

- **Greedy approach: Solving MILP problems**
  - Guarantee minimum resource used by each call
  - Computationally complex
- **Heuristic approach: Seeking the shortest paths**
  - Not guaranteed to use the minimum resources to serve a call
  - Computationally simple (e.g. Dijkstra's algorithm)

Question: Does system achieve optimal resource utilization if each call is served using the minimum resources?

MILP Formulation for PPFL

$$\text{Minimize} \quad \sum_{(i,j)\in L} c_{ij}x_{ij} + \sum_{(i,j)\in L} y_{ij}$$

$$\text{Subject to} \quad \sum_{(S,j)\in L} x_{Sj} - \sum_{(j,S)\in L} x_{jS} = \sum_{(j,D)\in L} x_{jD} - \sum_{(D,j)\in L} x_{Dj} = 1,$$

$$\sum_{(i,j)\in L} x_{ij} - \sum_{(j,i)\in L} x_{ji} = 0, \quad \forall i \neq S, D,$$

$$\sum_{(S,l)\in L} v_{ij}^{Sl} - \sum_{(l,S)\in L} v_{ij}^{lS} \geq x_{ij}, \quad \forall (S,l),(l,S),(i,j) \in L,$$

$$\sum_{(l,D)\in L} v_{ij}^{lD} - \sum_{(D,l)\in L} v_{ij}^{Dl} \geq x_{ij}, \quad \forall (D,l),(l,D),(i,j) \in L,$$

$$\sum_{(l,k)\in L} v_{ij}^{lk} - \sum_{(k,l)\in L} v_{ij}^{kl} = 0, \quad \forall (i,j) \in L, \forall k \neq S, k \neq D,$$

$$v_{ij}^{ij} + v_{ji}^{ij} = 0, \quad \forall (i,j) \in L,$$

$$y_{lk} \geq d_{ij}^{lk}(v_{ij}^{lk} - x_{lk}), \forall (i,j),(l,k) \in L,$$

$$x_{ij} \geq v_{ij}^{lk}, \quad \forall (i,j),(l,k) \in L,$$

$$x_{ij}, y_{ij}, v_{ij}^{lk} \in \{0,1\}, \forall (i,j),(l,k) \in L.$$

Example: Greedy vs. Shortest Path heuristic

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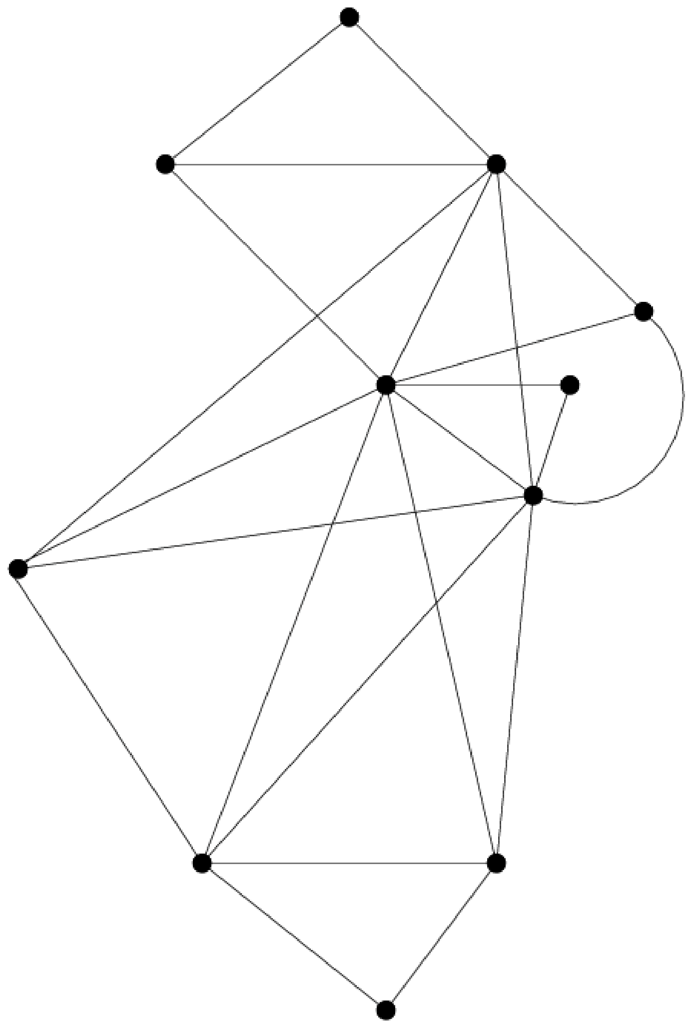
	SD Pair	Primary Path	Protection Path (protected link)	Total Number of Occupied Wavelengths
Greedy Approach	(1,4)	1-2-3-4	1-6-5-4 (1-2-3-4)	6 (no sharing)
	(6,3)	6-5-3	6-2-3 (6-5-3)	10 (no sharing)
	(3,5)	3-5	3-2-5 (3-5)	13 (no sharing)
Heuristic Approach	(1,4)	1-2-3-4	1-6-2-3-4 (1-2) 1-2-5-4 (2-3) 1-2-5-4 (3-4)	7 (share (2-3-4))
	(6,3)	6-5-3	6-2-3 (6-5) 6-2-3 (5-3)	10 (share (6,2))
	(3,5)	3-5	3-2-5 (3-5)	12 (share (2,5))

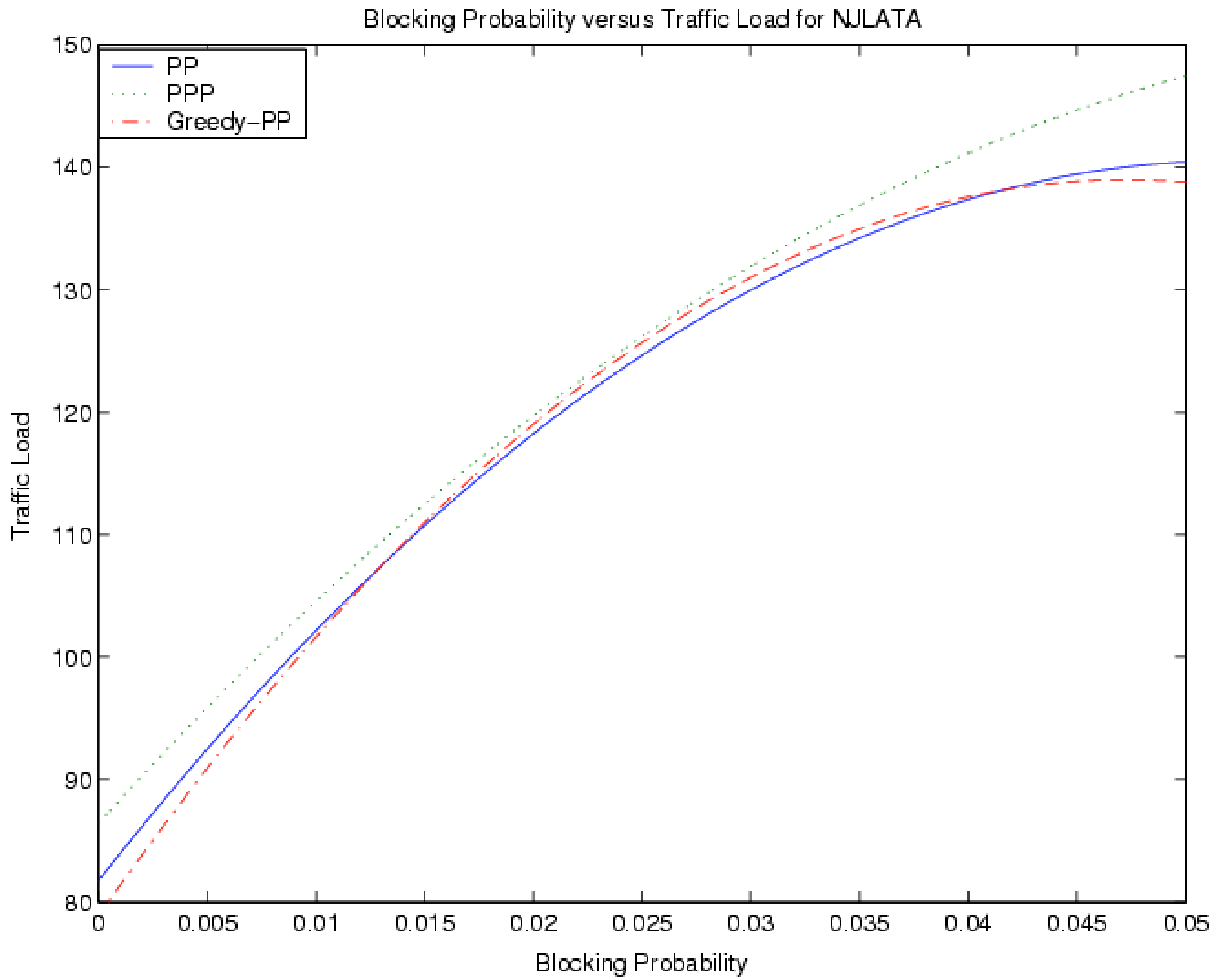
Shortest path heuristic may provide greater opportunity for future sharing of backup paths

Simulation: The 11 node, 21 link New Jersey Lata Network

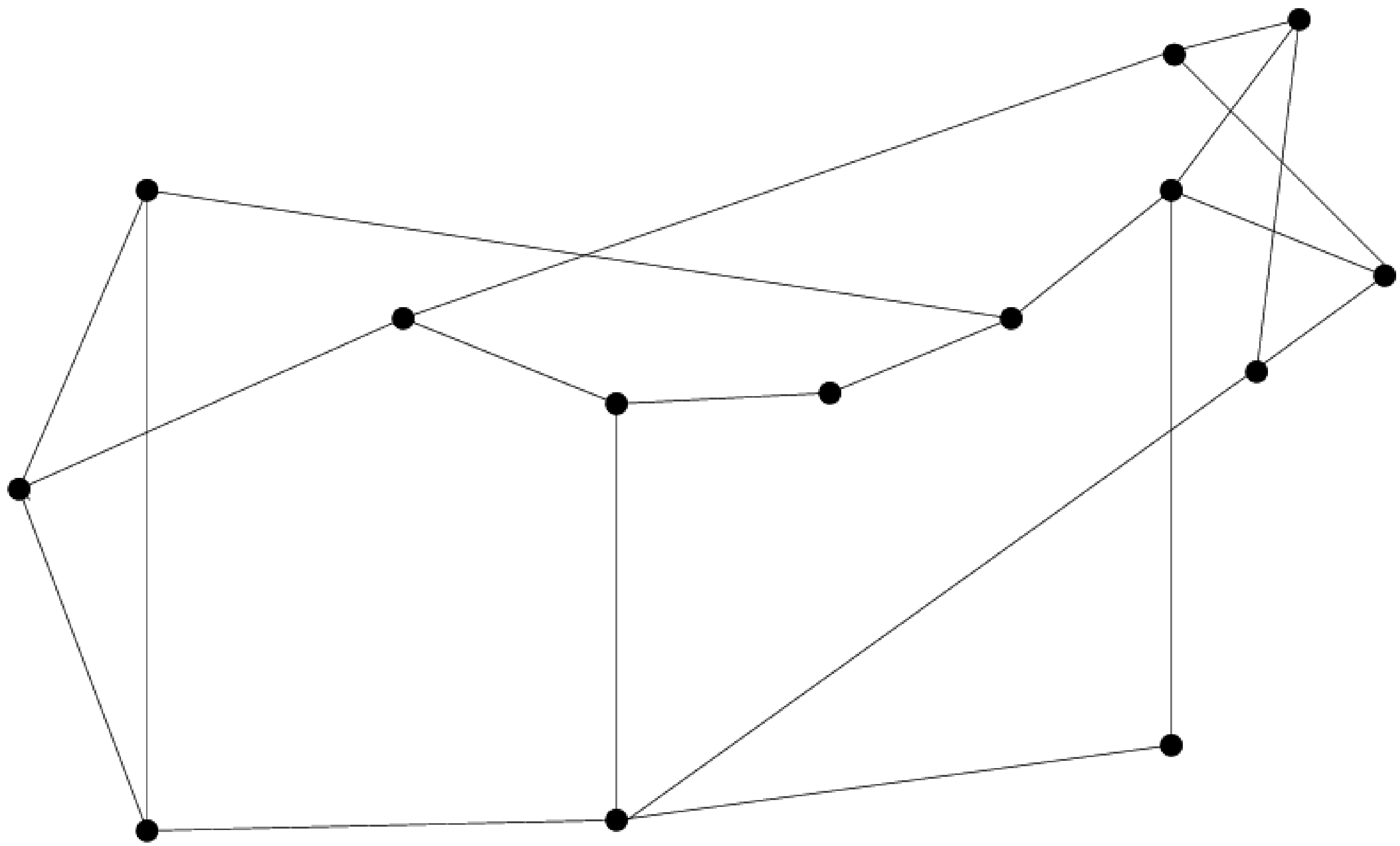


Simulation Results
Blocking Probability vs. Traffic Load

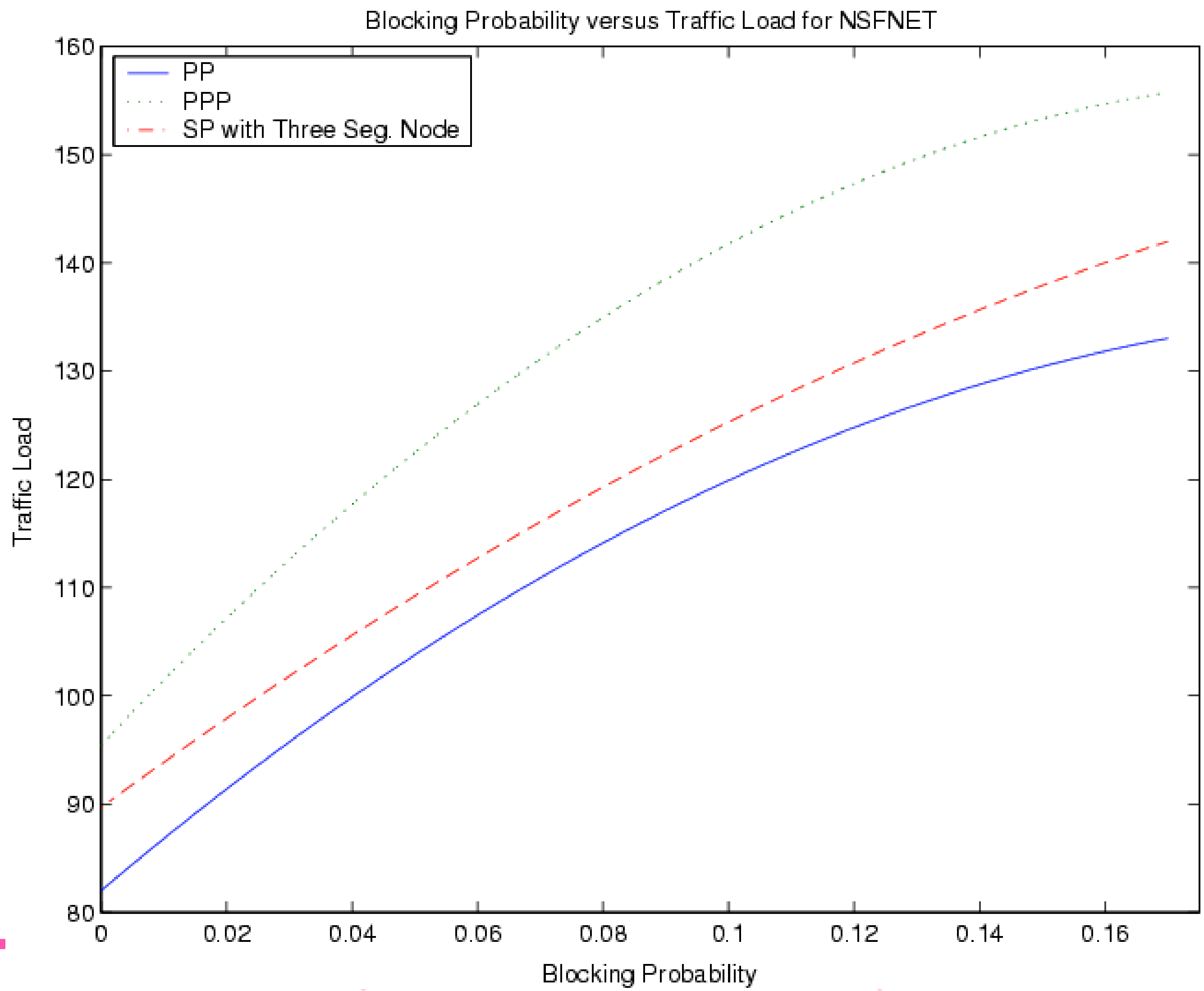
LIDS



Simulation: The 14 node, 21 link NSFNET Network



Simulation Results
Blocking Probability vs. Traffic Load



Discussion of results

- In the dynamic call-by-call case a greedy solution that finds the optimal routes at any point in time fails to take into account future calls

- In order to account for future call arrivals, the problem can be modeled as a Markov Decision Problem (e.g., dynamic programming)
  - Solution can be very complex

- Intuitive explanation:
  - The greedy solution treats primary and backup resources with equal importance and attempts to minimize their overall use
  - However, primary path resources cannot be shared whereas backup can
    - Better to minimize primary resources than backup resources
  - The shortest path approach puts a greater priority on minimizing the primary path resources

Discussion of path protection with failure localization (PPFL)

LIDS

- The PPFL scheme is more flexible than the path protection scheme
  - Path protection and link protection can be viewed as "solutions" to the PPFL scheme
  - Hence PPFL results in better resource utilization
- PPFL uses local failure information for finding protection paths
  - This added information requires more sophisticated network management
- The call-by-call model leads to dynamic resource allocation scheme that cannot be solved using a traditional ILP approach
  - Markov Decision formulation - too complex
  - Simple heuristics - e.g., shortest path

Summary

- **Cross-Layer optimization is critical to the design of protection algorithms for WDM based networks**
  - ***Survivable routing of logical topologies:*** **How do we embed the logical topology on a physical topology so that the logical topology can withstand physical link failures**
  - ***Physical topology design:*** **How do we design physical topology so that they can be used to embed rings in a survivable manner**
  - ***Path protection with failure localization:*** **What are the benefits of failure localization for efficient path protection?**