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Performance from Experience

Maximizing the Transparency Advantage in Optical Networks

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Opening Comments

- Transparency is generally regarded as desirable
- End-to-end transparency for all paths may not always be possible
- Some plausible design paradigms for (mostly) transparent networks:
  - Island-based designs
    - Partition network into "well-behaved" islands with OEO at the "edges"
    - Restrictive design paradigm can make routing easier
    - Restrictive approaches can be wasteful of resources
    - Restrictions may be violated as network evolves over time
  - Unstructured designs
    - OEO nodes are placed "strategically" throughout the network
  - Distributed regeneration (selective regeneration)
    - Every transparent network element may have limited OEO regeneration capabilities to be used *as needed*

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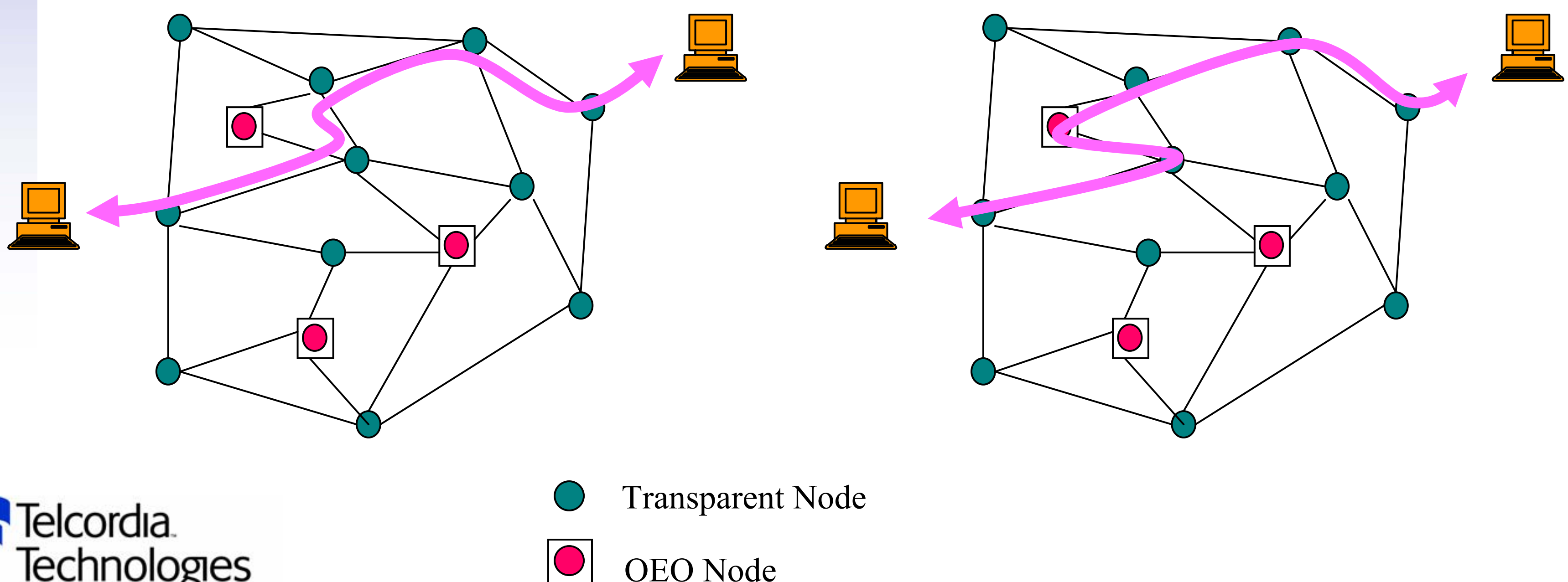
Design & Routing Challenges

- Design challenge: where do we provide OEO regeneration?
- Routing challenge: given a network with OEO regeneration in place, how do we “find” it when needed?
- *Signal impairments* place limits on feasible lightpaths and designs
  - constrain the number of consecutive transparent nodes in a path
  - constrain the distance between OEO nodes in a path



Design Strategy for Unstructured Networks

- Our Assumptions:
  - Nodes are either opaque or transparent
  - Only opaque nodes perform OEO regeneration
  - Transparent nodes are cheaper
- The Problem: select the smallest set of opaque nodes that still provides at least one impairment-feasible path between each pair of nodes
- Two Solutions:
  - a more traditional path improvement heuristic
  - a new approach that formulates and solves a connected dominating set problem on a related graph that assures:
    - each transparent node can reach at least one opaque node
    - opaque nodes can communicate along impairment-feasible routes
- Features:
  - Solutions require very few OEO nodes because we assure the existence of paths without assuring specific paths
  - Solutions assure a general topological feasibility property
  - Approach can be translated into intuitively appealing “design rules”

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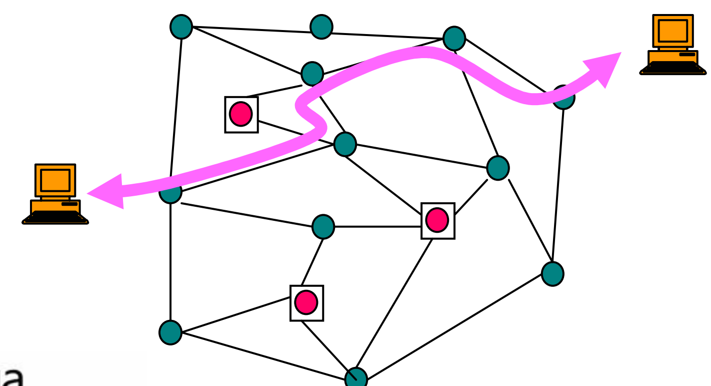
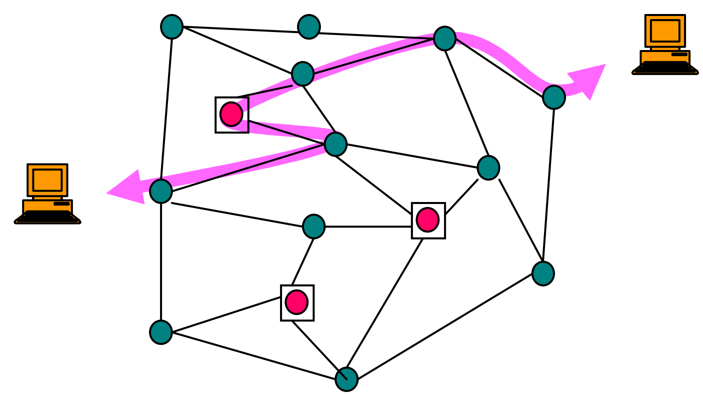
Routing Algorithms

- Given an OEO placement that does not assure that every path is feasible, a routing algorithm must identify impairment-feasible paths
  - explicitly monitor consecutive transparent nodes and distance
  - explicitly model the restorative effect of regeneration by OEO
  - guaranteed to find an impairment-feasible path if one exists
  - Developed algorithm can be extended to:
    - make “decisions” about whether or not to regenerate at OEO nodes
    - select an impairment-aware path that requires fewest regenerations
    - select an impairment-feasible path that requires fewest added transponders
    - consider constraints on additional metrics



“shortest path”



impairment-feasible path
if node limit =3

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Design 1: A Path Improvement Heuristic

Generate a path between each pair of nodes

Place OEO nodes to improve infeasible paths until all paths become feasible

- In each iteration put OEO capability at location that:
  - makes most new paths feasible
  - improves the most infeasible paths
  - is on the most paths

- Guarantees the feasibility of a specific set of paths
  - Assumes a coupling between design and provisioning
- Typically places more OEOs than needed to guarantee the existence of feasible paths
- Allows flexibility to include “path-specific” properties

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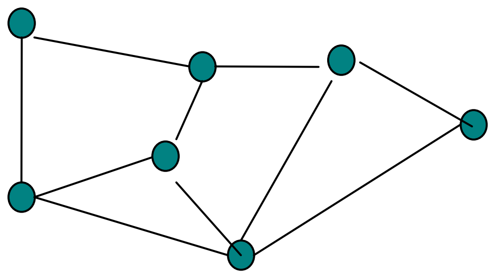
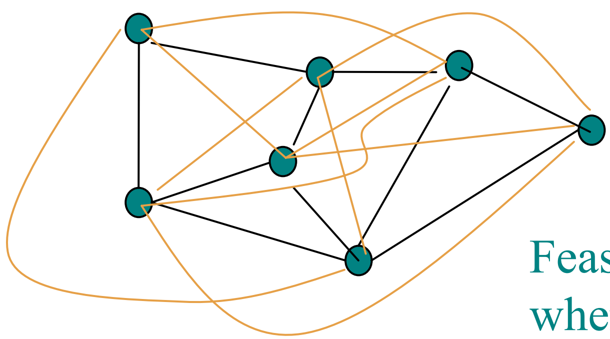
Design 2: A New Approach

- View feasibility more generally:
  - Make sure that every transparent node can reach at least one OEO node along an impairment-feasible path
  - Make sure that OEO nodes can communicate with each other along impairment-feasible paths
  - If above are true, a feasible route exists between each pair of nodes
- Feasibility can be represented on a “feasibility graph”



Original network

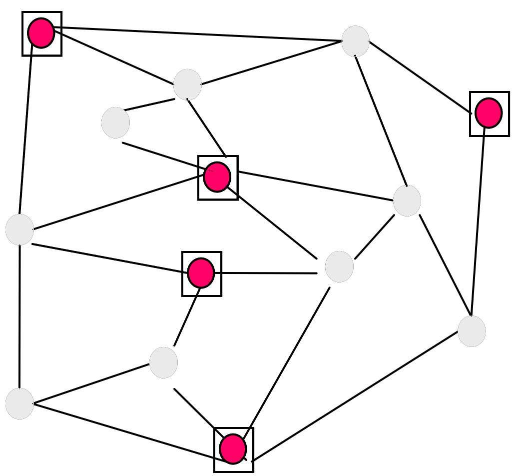


Feasibility graph when node limit = 2

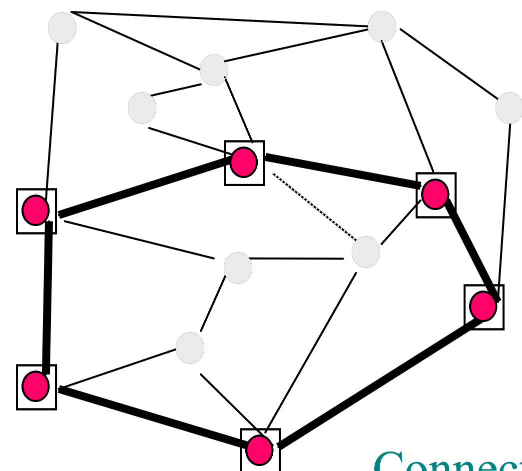
- As long you place OEOs so that every transparent node has a link to an OEO node in the feasibility graph, the first requirement is assured

The Connected Dominating Set Problem

- The Connected Dominating Set Problem:
  - Select a set minimum size set of (OEO) nodes such that every node *not in* the set has a link to a node *in* the set...
    - The selected set is a dominating set
    - This assures that each transparent node reaches an OEO node
  - …and such that if we remove all nodes not in the set the remaining graph is connected
    - The selected set is a connected dominating set
    - This assures that OEO nodes can feasibly communicate

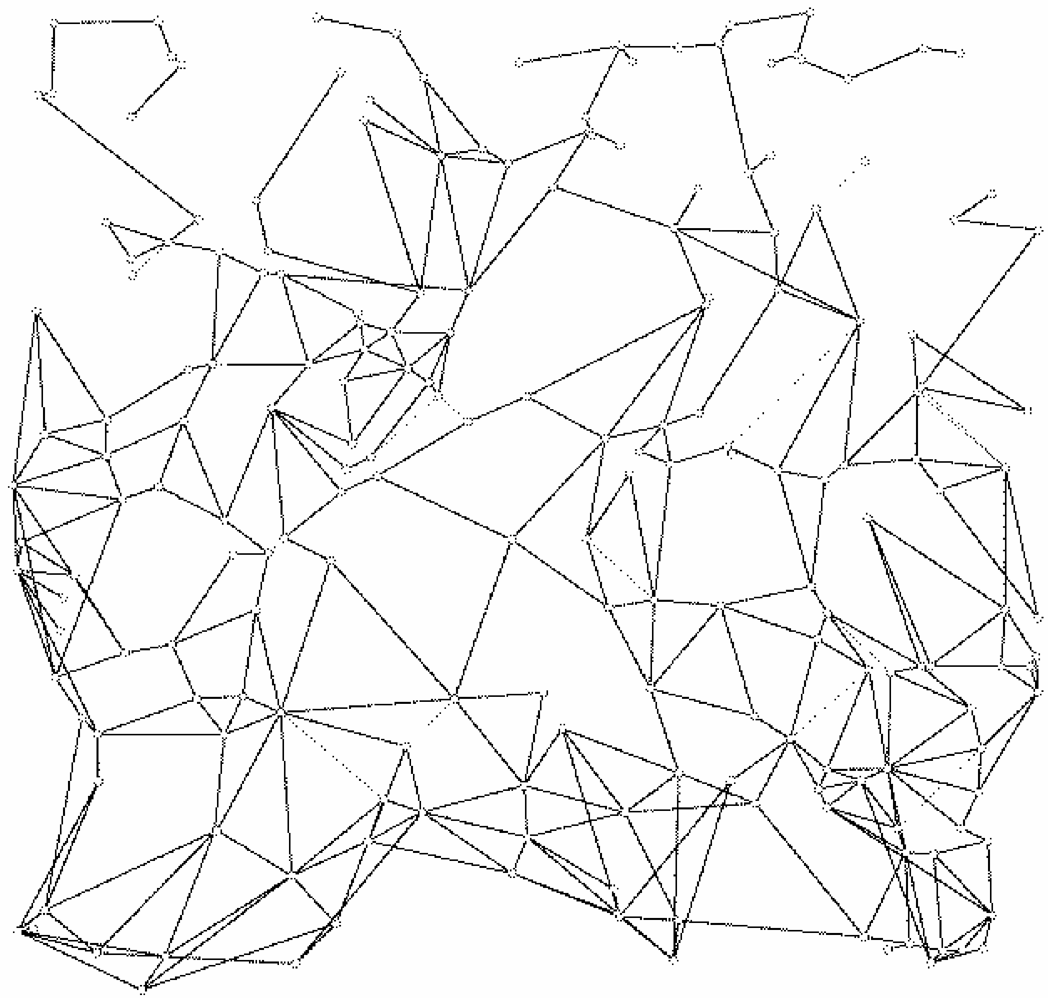


Dominating Set



Connected Dominating Set

Test Network



200 nodes
361 links

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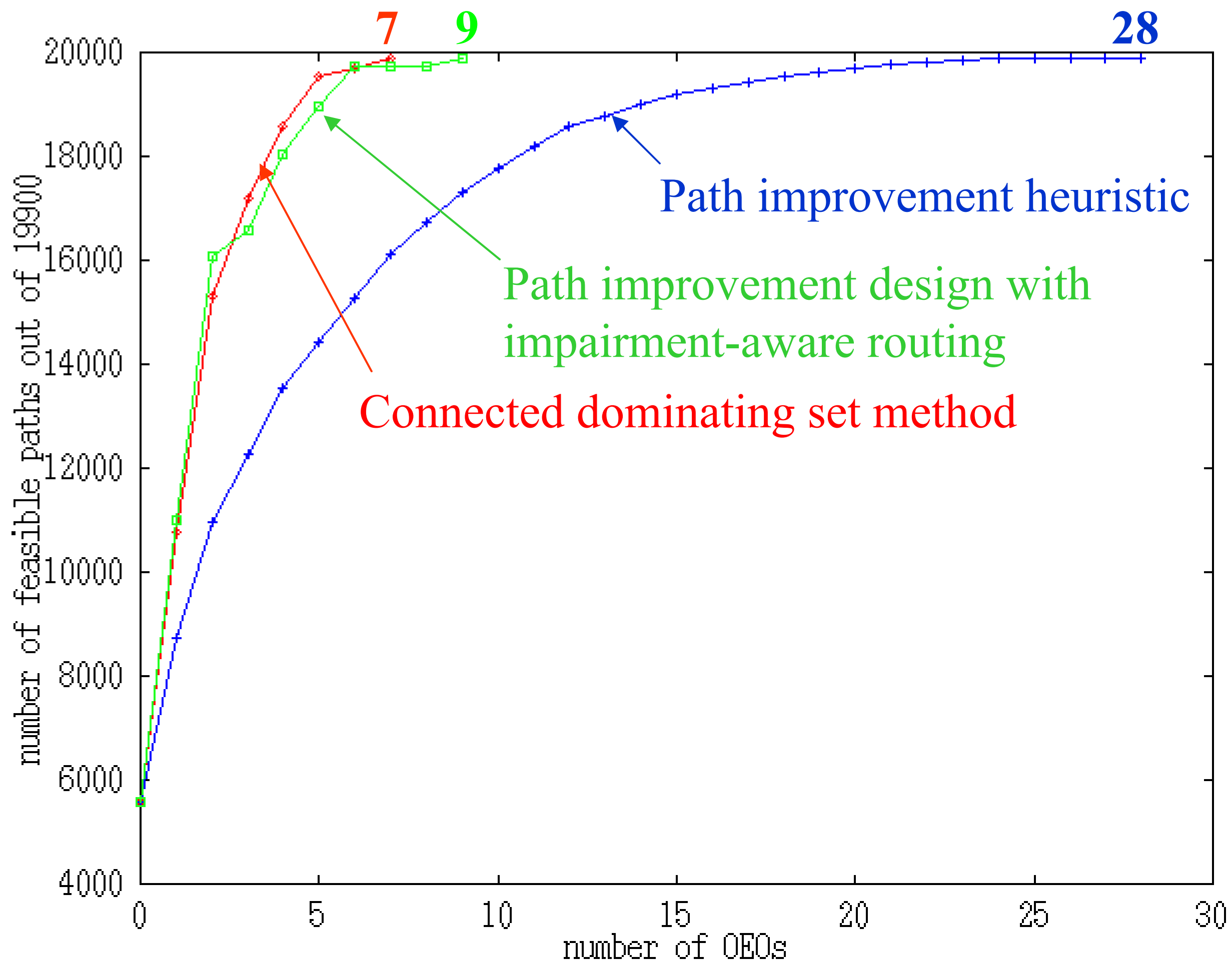
Results for 200 Node Network

Transparent node limit = 6 **Distance limit = 170km**



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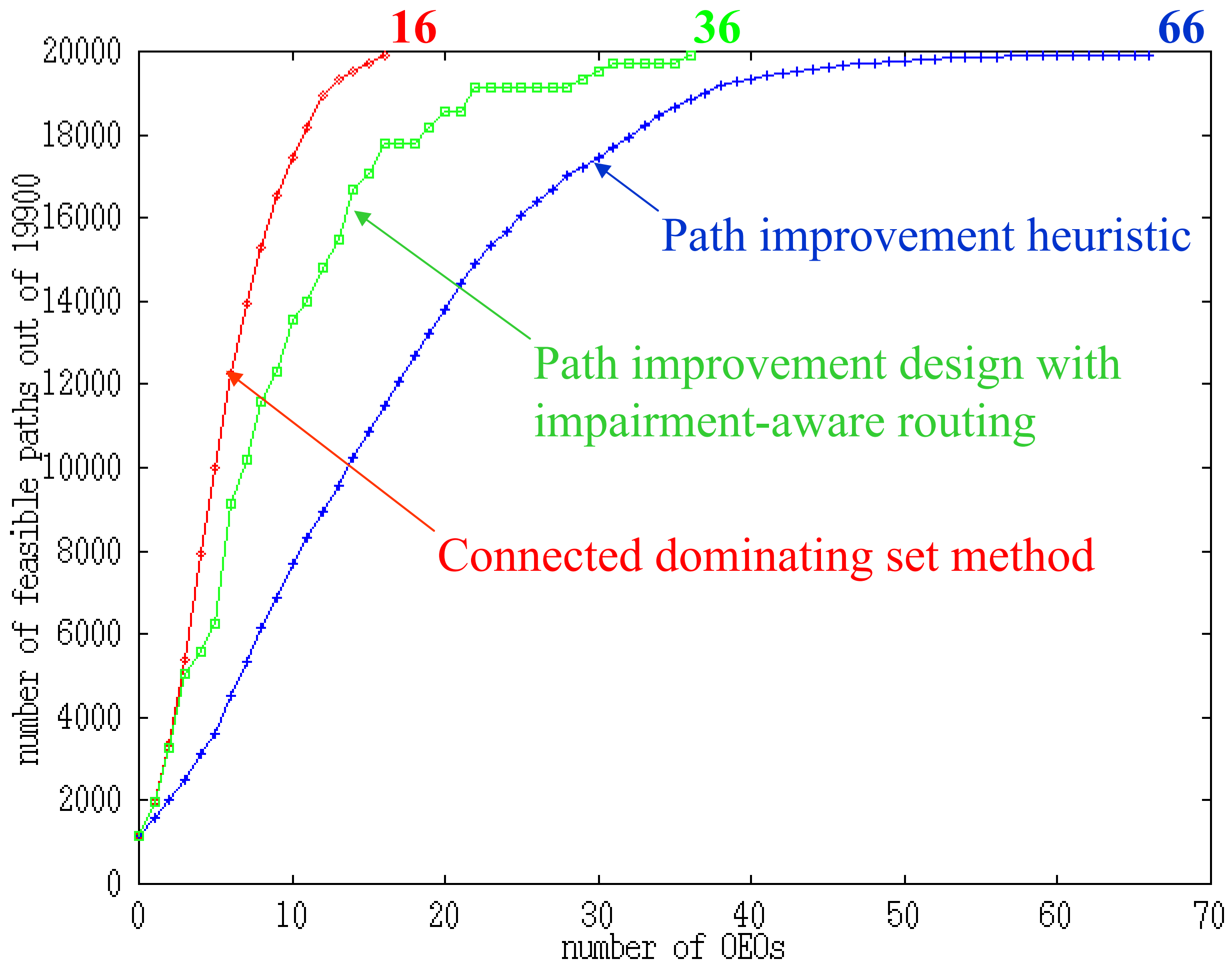
Results for 200 Node Network

Transparent node limit = 3 **Distance limit = 80km**



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Concluding Comments

- Assuring that feasible paths exist requires very few OEO sites
  - Feasibility was assured with only 7 OEO nodes
- Extracting the most benefit from sparse regeneration requires impairment-aware routing
  - With “unaware” minimum hop routing, we need 28 OEO sites
  - This assumes *tight coupling* between design and routing
- Sparsely located regeneration will lengthen end-to-end paths
  - The effect will be to increase the number of OEOs performed and the number of required transponders
- The connected dominating set method:
  - provides a basic feasibility guarantee with very few OEO nodes
  - provides a test that can be applied to any placement