Minimal Wavelength Assignment in Survivable Mesh Networks

Richard S. Barr

Mark W. Lewis

Southern Methodist University

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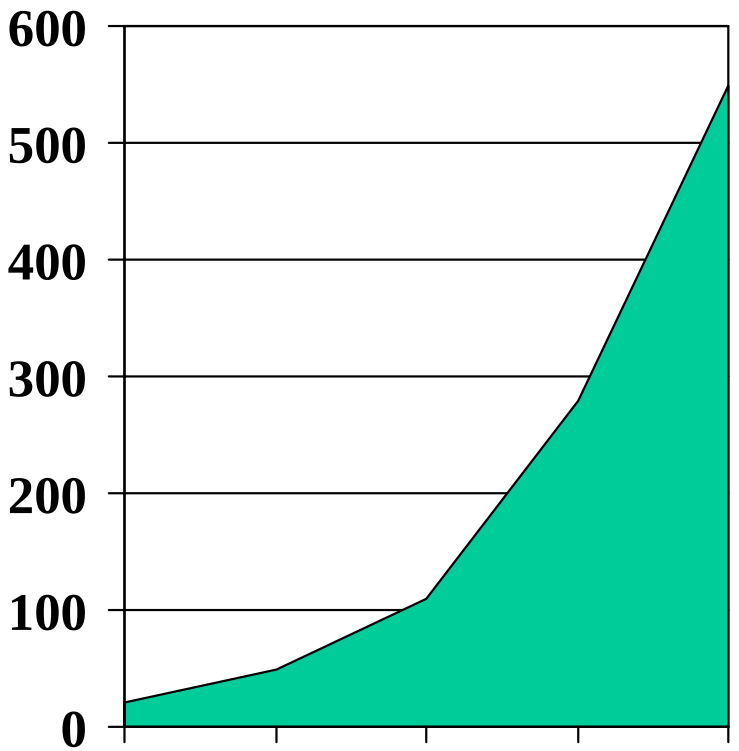
Telecommunications Networks

- Exponential growth in services demand
- Competitive forces on providers
- Creates pressure for greater efficiencies & backbone network capacity

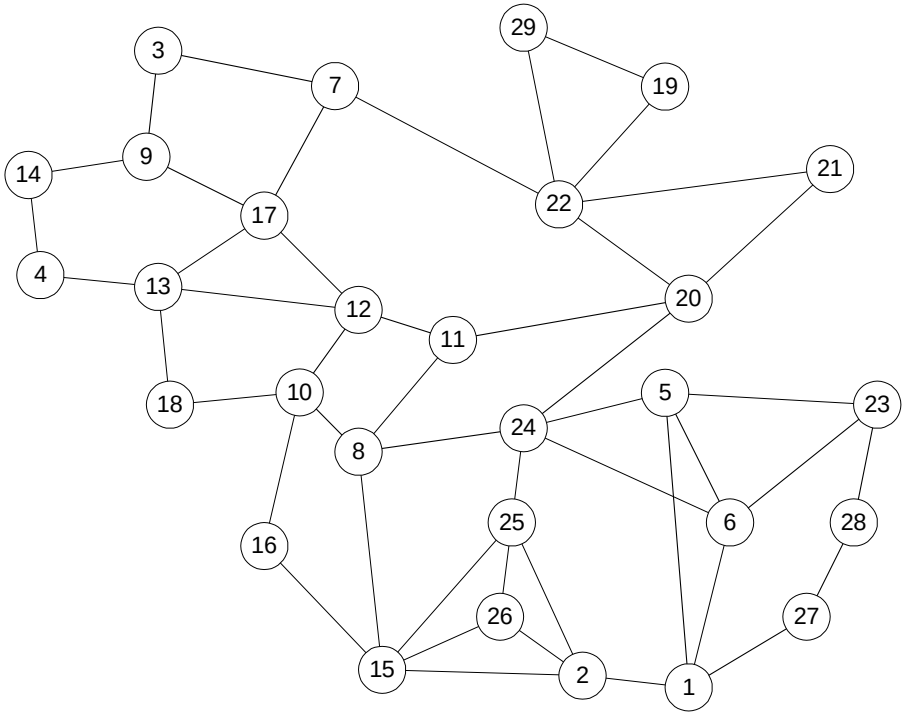


Backbone Network Design

- Designing telecom networks involves:
  - Using existing, building new net links
  - Selecting equipment
  - Routing demand over given topology
- A wide range of optimization problems
  - Variety of topologies: rings, ATM, wireless
  - Linear, DXC, WDM, DWDM

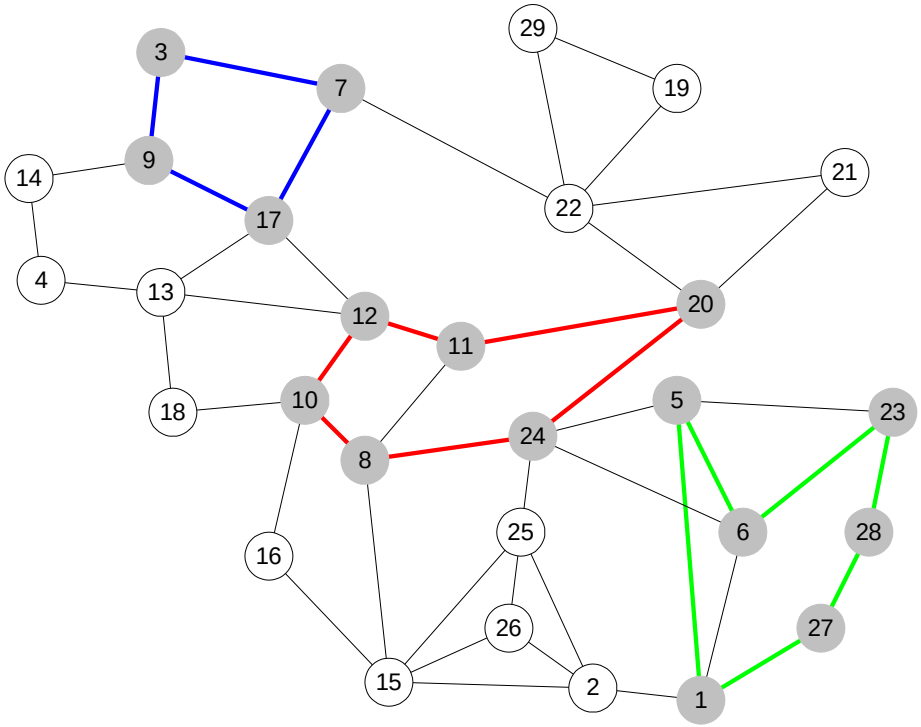
Network Design Problem

- Given:
  - Network of nodes, fiber-optic links
  - Demand matrix
    - Dedicated bandwidth between some or all pairs of nodes
- Required:
  - Link capacities
  - Demand routing
  - Equipment



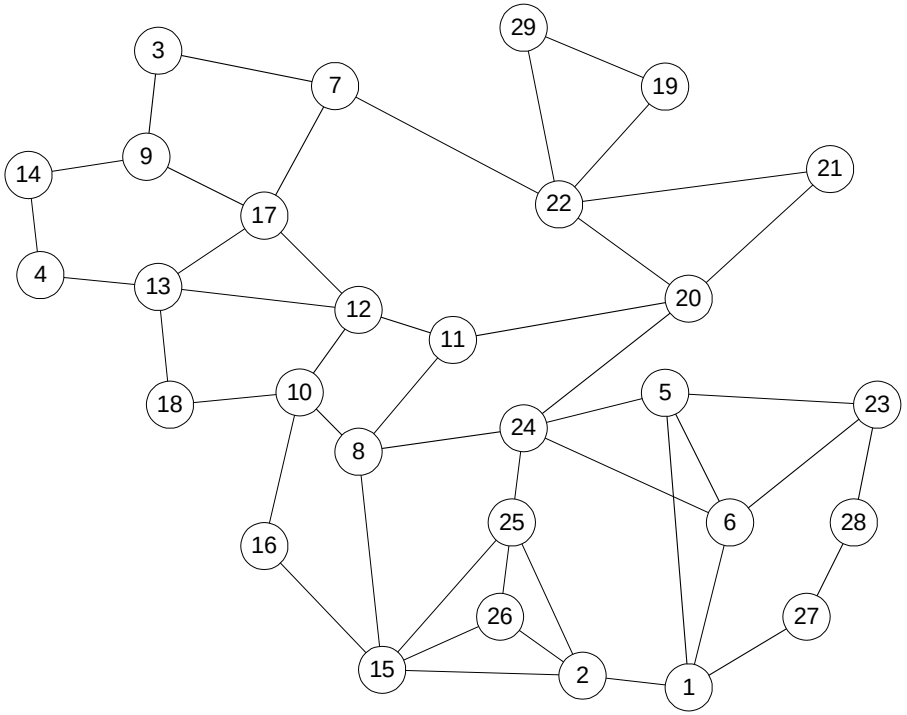
Network Design Approaches

- Primary network topologies: *ring* and *mesh*
- *SONET Ring designs*
  - A series of (connected) rings
  - Automatic recovery from a single link failure
  - The industry standard



Network Design Approaches

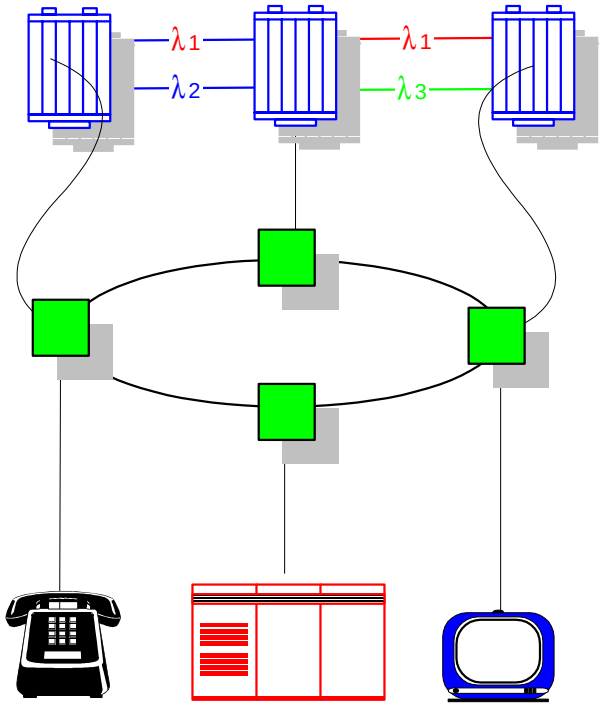
- *Mesh topologies* use:
  - Point-to-point demand working paths
  - Alternate demand restoration paths for rerouting at link failure
- Typically require less spare bandwidth than ring designs



All-Optical Networks

- SONET's use of electronics limits capacity
- All-Optical Network (AON) technology
  - Uses Wave-Division Multiplexing (WDM)
  - Transmits multiple signals over an *existing* fiber line using different wavelengths (λs)
  - Not limited by electronic circuitry
  - Can increase line capacity by 100X - 10,000X
  - Provide same restorability protection as SONET

Network Transport Layers



All-Optical Layer
- Mesh designs prevalent
- (Dense) wave-division multiplexing
- High-level restoration

Sonet Layer
- High-speed protection
- Time-division multiplexing
- Time-slot grooming

Services Layer
- Delivery of services to end user

(Source: T. Krause, Telephony, April 21, 1997)

Designing Mesh Networks

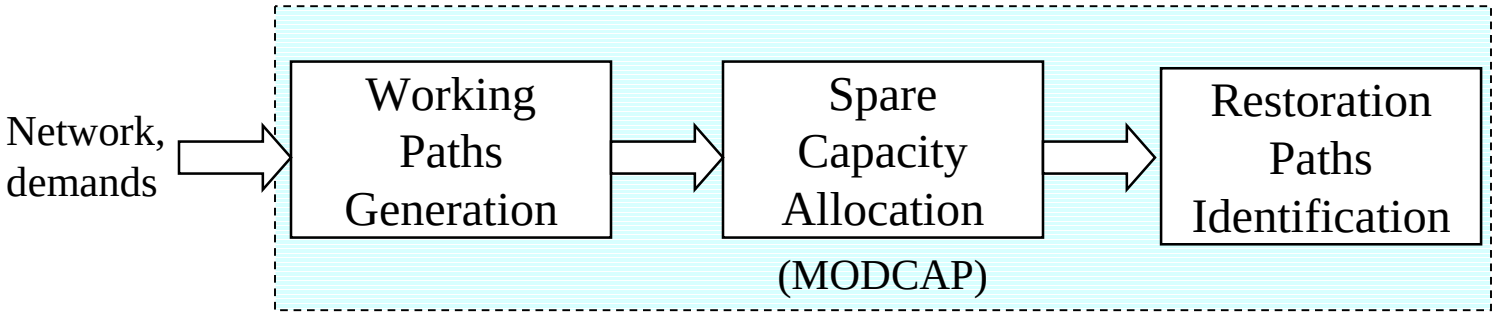
Survivable Mesh Networks

- Overlaying an all-optical mesh on a ring topology provides both quick recovery and lower cost

- A survivable mesh network requires:
  - Location of spare link capacities
  - Working and restoration paths for all demand

Problem Decomposition

- Kennington & Lewis approach:



Minimum Modular Spare Capacity Allocation

- MODCAP (Modular Capacity) software by Kennington and Lewis
  - Determine the minimum spare capacity needed to recover from any single-link failure
  - Capacity is allocated in modular amounts
    - Our special case: multiples of base unit (OC-x)
    - Capacity is allocated on a link-by-link basis

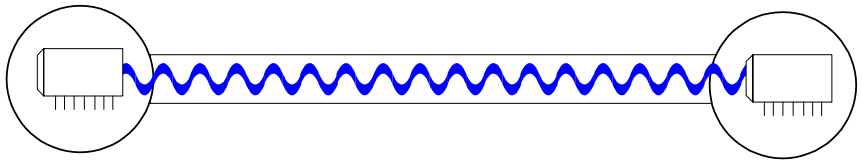
Finding Restoration Paths

- Single Integral Path for Restoration (SPIR) software (Kennington & Lewis)
  - Determines a single restoration path for an OD pair affected by a link failure
  - Single restoration paths correspond to the “ring over mesh” topology
- Wavelength conflicts may be generated here
  - Paths are not necessarily diverse

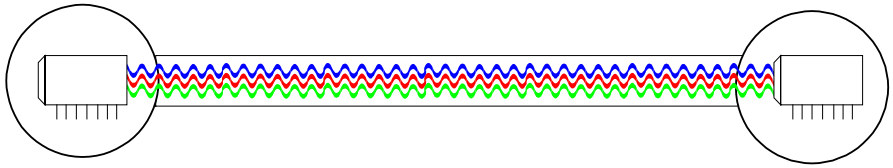
Designing All-Optical Mesh Networks

All-Optical Networks Use WDM

- Historically:
  - Links consist of 1+ fiber-optic cables
  - Each fiber carries one signal



- Wave-Division Multiplexing allows multiple signals per fiber line
  - Each signal is assigned a different frequency, light wavelength, color, or λ



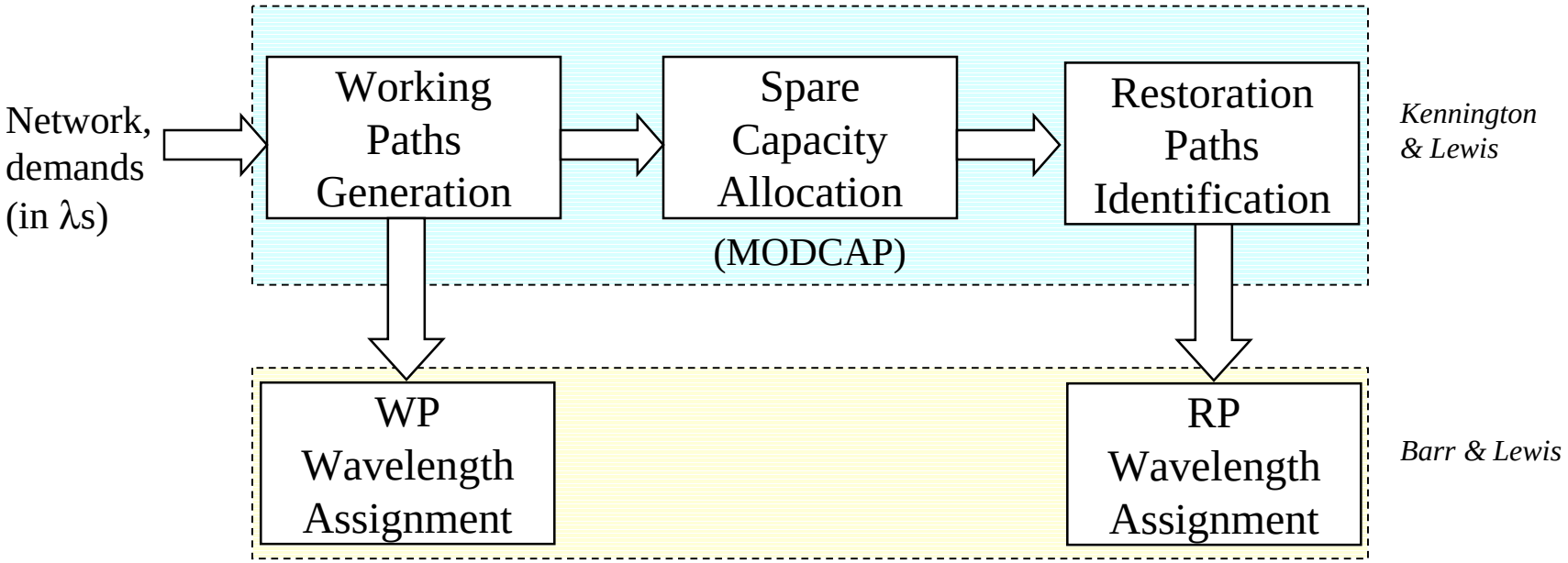
WDM Can Complicate Design

- Traffic routed between an origin and destination uses a unique wavelength throughout its path
- How are wavelengths assigned to avoid conflicts over a link?

Survivable Mesh Network Wavelength Assignment Problems

- Given
  - Mesh network
  - Demands (in # of wavelengths per OD)
- Required
  - Wavelength assignments for the working and restoration paths
  - Total number of wavelengths minimized

Problem Decomposition



Wavelength Assignment Problem

- View wavelengths as colors
  - Each demand unit is assigned a color on its path
  - Path is a set of edges connecting O-D pair
- No edge can use the same color for its carried demands
- Simple cases = graph coloring problems
  - NP-hard
  - Efficient heuristics have been developed

Assumption

- No optical packet switching
  - Optical cross connects (OCXs) coming soon
  - Related problem: placement of OCXs and wavelength converters in a DWDM network
  - Every origin-destination pair views their working-path wavelength(s) as dedicated

Restoration Path Wavelength Assignment

- Restoration paths are assigned wavelengths from the set of available wavelengths
  - Failed link will free certain working-path wavelengths
- Edge failures considered independent
  - Restoration paths from different edge failures can use the same color on a link
  - No working path conflicts are allowed

Global Minimal Wavelength Model

- Restore demand, using one unique λ per restoration path, favoring smaller order λ.

$$\min \sum_{e \in E} \sum_{k \in C^e} \sum_{\lambda \in A^k} \lambda \, f_k^{e\lambda}$$

s.t.

$$\sum_{\lambda \in A^k} f_k^{e\lambda} = d_k^e \qquad \forall e \in E, \forall k \in C^e$$

$$\sum_{\substack{k \in C^e \ni i \in k \\ \text{and } \lambda \in A^k}} f_k^{e\lambda} \leq 1 \qquad \forall e \in E, \forall i \in E \setminus \{e\}, \forall \lambda \in A^k$$

$$f_k^{e\lambda} \in \{0, 1\} \qquad \forall e \in E, \forall k \in C^e$$

Global RP Wavelength Model

- $f^{e\lambda}_{k}$ = {0,1} assign λ to path *k* when *e* fails
- λ = wavelength number (1,2,…)
- Consider all RPs simultaneously

Minimize weighted sum of *f*s

s.t. Meet each demand, d^{e}_{k}

Without color clashes

Serial Decomposition Algorithm

- Global model
  - Only small models could be solved with Cplex
  - Used 2000 seconds, Cplex 6
- Heuristic: solve for each edge failure separately, using a Serial Assignment model
  - Emphasizes wavelength re-use
  - Solves edges with largest number of RPs first

Serial Assignment Model

- For a given failed edge *e*, restore demands C^e using a unique λ, favoring λ which have been used previously.

$$\min \sum_{k \in C^e} \sum_{\lambda \in A^k} \begin{cases} 0.5\, f_k^\lambda & \text{if } \lambda \in \{\lambda : \forall_i \in k, \lambda \in L_i\} \\ \lambda\, f_k^\lambda & \text{otherwise} \end{cases}$$

s.t.

$$\sum_{\lambda \in A^k} f_k^\lambda = d_k^e \qquad \forall k \in C^e$$

$$\sum_{\substack{k \in C^e \ni i \in k \\ \text{and } \lambda \in A^k}} f_k^\lambda \leq 1 \qquad \forall i \in E \backslash \{e\}, \forall \lambda \in A^k$$

$$f_k^\lambda \in \{0, 1\} \qquad \forall k \in C^e$$

Global vs. Decomposition

- On small (10-node) problems
  - Decomposition was two orders of magnitude faster
  - Results were almost identical

Overall Results

- A typical 50-node problem with 200 demands and average node degree of 2.5
  - Working path assignment in ~50 sec (coloring heuristic)
  - Restoration path assignment in ~100 sec (serial decomposition heuristic)

  600 MHz Alpha with 98 MB memory available, using CPLEX 6.01
- The corresponding global minimization model instance requires >98 MB memory

Conclusions

- DWDM creates challenging bandwidth management problems
- The global wavelength assignment model can produce large, challenging problem instances
- Decomposition of the survivable network wavelength assignment problem works well

Future Work

- Reducing wavelength conflicts created during restoration path discovery
- Combining working and restoration path wavelength assignment