Minimal Wavelength Assignment in Survivable Mesh Networks

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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 $\lambda$
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

- Working Paths Generation
- Spare Capacity Allocation (MODCAP)
- Restoration Paths Identification

Network, demands (in $\lambda$s)

WP Wavelength Assignment

RP Wavelength Assignment

Kennington & Lewis

Barr & Lewis
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 $\lambda$ per restoration path, favoring smaller order $\lambda$.

$$\begin{align*}
\min & \quad \sum_{e \in E} \sum_{k \in C^e} \sum_{\lambda \in \Lambda^k} \lambda \ f_k^{e\lambda} \\
\text{s.t.} & \quad \sum_{\lambda \in \Lambda^k} f_k^{e\lambda} = d_k^e \quad \forall e \in E, \forall k \in C^e \\
& \quad \sum_{k \in C^e \land i \in k} f_k^{e\lambda} \leq 1 \quad \forall e \in E, \forall i \in E \setminus \{e\}, \forall \lambda \in \Lambda^k \\
& \quad f_k^{e\lambda} \in \{0, 1\} \quad \forall e \in E, \forall k \in C^e
\end{align*}$$
Global RP Wavelength Model

- \( f_{e}^{\lambda}_{k} = \{0,1\} \) assign \( \lambda \) to path \( k \) when \( e \) fails
- \( \lambda = \) wavelength number (1,2,\ldots)
- 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 $\lambda$, favoring $\lambda$ which have been used previously.

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

s.t.

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

$$\sum_{k \in C^e \land i \in k \land \lambda \in A^k} f_k^\lambda \leq 1 \quad \forall i \in E \setminus \{e\}, \forall \lambda \in A^k$$

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