Routing and Wavelength Assignment for Wavelength-Routed WDM Networks

- Combined routing and wavelength assignment problem
- Routing
  - static: ILP formulation
  - dynamic: on-line algorithms
- Wavelength assignment
  - static: graph coloring approach
  - dynamic: heuristics
- A new wavelength assignment heuristic
RWA

- Problem statement
- Wavelength-continuity constraint
Combined Routing and Wavelength Assignment Problem

Minimize: \[ F_{\text{max}} \]

such that

\[ F_{\text{max}} \geq \sum_{s,d,w} F_{ij} \quad \forall \ ij \]

\[ \sum_i F_{ij}^{sdw} - \sum_k F_{jk}^{sdw} = \begin{cases} -\lambda_{sdw} & \text{if } s = j \\ \lambda_{sdw} & \text{if } d = j \\ 0 & \text{otherwise} \end{cases} \]

\[ \sum_w \lambda_{sdw} = \Lambda_{sd} \]

\[ F_{ij}^{sdw} = 0, 1 \]

\[ \sum_{s,d} F_{ij}^{sdw} \leq 1 \]
Routing - ILP Formulation

Minimize: \( F_{\text{max}} \)

such that

\[
F_{\text{max}} \geq \sum_{s,d} F_{ij}^{sd} \forall \ ij
\]

\[
\sum_i F_{ij}^{sd} - \sum_k F_{jk}^{sd} = \begin{cases} 
-\lambda_{sd} & \text{if } s = j \\
\lambda_{sd} & \text{if } d = j \\
0 & \text{otherwise}
\end{cases}
\]

\[
\lambda_{sd} = 0, 1
\]

\[
F_{ij}^{sd} = 0, 1
\]
Routing - Algorithms For Dynamic Traffic

- Fixed routing (On/Off line)
- Fixed-alternate routing (On/Off line)
- Adaptive routing (On line)
  - adaptive shortest path routing
  - least congested path routing
Wavelength Assignment with Known Lightpaths and Routes - Graph Coloring

- Construct an auxiliary graph $G(V,E)$
- Color the nodes of the graph $G$ such that no two adjacent nodes have the same color
- Sequential graph coloring approaches
Wavelength Assignment Heuristics

- Random
- First-Fit
- Least-Used/SPREAD
- Most-Used/PACK
- Min-Product
- Least Loaded
- MAX-SUM
- Relative Capacity Loss
- Wavelength Reservation
- Protecting Threshold
Illustrative Example

Note: control network not shown. All wavelengths shown are for data traffic.
Calculation of Max-Sum

Wavelengths: P₁:(2,4)

<table>
<thead>
<tr>
<th>λ₀</th>
<th>λ₁</th>
<th>λ₂</th>
<th>λ₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Wavelength-path Capacities:

- λ₀: 01
- λ₁: 10
- λ₂: 01
- λ₃: 10

WPC: Wavelength-path Capacity

Total WPC Loss:

- P₂:(1,5) WPC Loss:
  - λ₀: 1
  - λ₁: 0
  - λ₂: 1
  - λ₃: 0
  - Total: 2

- P₃:(3,6) WPC Loss:
  - λ₀: 0
  - λ₁: 1
  - λ₂: 0
  - λ₃: 0
  - Total: 1

- P₄:(0,3) WPC Loss:
  - λ₀: 0
  - λ₁: 0
  - λ₂: 1
  - λ₃: 1
  - Total: 1

Selected: λ₀, λ₁, or λ₃
Calculation of Relative Capacity Loss

Wavelengths

\( \lambda_3 \)
\( \lambda_2 \)
\( \lambda_1 \)
\( \lambda_0 \)

P1:(2,4)

Wavelength selected: \( \lambda_1 \) or \( \lambda_3 \)

RCL of each path on each \( \lambda \)

<table>
<thead>
<tr>
<th>Wavelengths</th>
<th>( \lambda_3 )</th>
<th>( \lambda_2 )</th>
<th>( \lambda_1 )</th>
<th>( \lambda_0 )</th>
<th>P2:(1,5)</th>
<th>P3:(3,6)</th>
<th>P4:(0,3)</th>
<th>Total RCL</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_3 )</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>( \lambda_2 )</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>( \lambda_1 )</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>( \lambda_0 )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

ECS 259 -- H. Zang and B. Mukherjee, UC Davis
Simulation Network

Connection management protocol: link-state
Results from Others’ Publication


20-node unidirectional ring, load/W = 1 Erlang

5x5 bidirectional mesh-torus, load/W = 25 Erlangs
Computational Complexity

- Wavelength reservation & Protecting threshold - constant
- Random & First-Fit - $O(W)$
- Min-Product & Least-Loaded - $O(NW)$
- Least-Used & Most-Used - $O(LW)$
- Max-Sum & Relative Capacity Loss - $O(WN^3)$

where $W$ - # of wavelengths, $N$ - # of nodes, $L$ - # of links
Distributed RCL Algorithm

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Subtotal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_3$</td>
<td>0</td>
<td>1/3</td>
<td>0</td>
<td>1/4</td>
<td>1/4</td>
<td>1/3</td>
<td>0</td>
<td>11/12 *</td>
</tr>
<tr>
<td>$\lambda_2$</td>
<td>0</td>
<td>1/3</td>
<td>0</td>
<td>1/4</td>
<td>1/4</td>
<td>1/3</td>
<td>1/2</td>
<td>17/12</td>
</tr>
<tr>
<td>$\lambda_1$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1/4</td>
<td>1/4</td>
<td>1/3</td>
<td>1/2</td>
<td>13/12</td>
</tr>
<tr>
<td>$\lambda_0$</td>
<td>1</td>
<td>1/3</td>
<td>0</td>
<td>1/4</td>
<td>1/4</td>
<td>0</td>
<td>0</td>
<td>19/12</td>
</tr>
</tbody>
</table>

RCL table at Node 2

* Wavelength selected: $\lambda_3$
Characteristics of Distributed RCL

- Less state information is exchanged
- Faster computation of wavelength assignment upon a connection request
- Can be combined with adaptive routing
Simulation Network

- Average propagation delay between two nodes: 0.107 ms
- Average hop distance: 1.53
Comparison of DRCL with adaptive routing and RCL with fixed routing
## Conclusion for RWA

<table>
<thead>
<tr>
<th>Heuristics</th>
<th>Complexity</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Least Used</td>
<td>$O(LW)$</td>
<td>Ordered in increasing order</td>
</tr>
<tr>
<td>Random</td>
<td>$O(W)$</td>
<td></td>
</tr>
<tr>
<td>Min-Product</td>
<td>$O(NW)$</td>
<td></td>
</tr>
<tr>
<td>First-Fit</td>
<td>$O(W)$</td>
<td></td>
</tr>
<tr>
<td>Most-Used</td>
<td>$O(NW)$</td>
<td></td>
</tr>
<tr>
<td>Least-Loaded</td>
<td>$O(LW)$</td>
<td></td>
</tr>
<tr>
<td>Max-Sum</td>
<td>$O(WN^3)$</td>
<td></td>
</tr>
<tr>
<td>Relative Capacity Loss</td>
<td>$O(WN^3)$</td>
<td></td>
</tr>
</tbody>
</table>

$L$: # of links, $N$: # of nodes, $W$: # of wavelengths
Future Research

- Survivable wavelength-routed WDM networks
  - previous work: static traffic & single link failure [S. Ramamurthy 1998]
  - higher layer protection - logical topology design with bundle cut in mind
  - WDM layer protection - dynamic traffic
Future Research (Cont’d)

- Managing multicast connections in wavelength-routed WDM networks
  - KMB
  - Bellman-Ford
  - Chain