Reliability, Availability, Survivability: Protection & Restoration

Overview

- **Reading**: Connection management for survivable wavelength-routed WDM mesh networks
- **Outline**
  - Classification of survivable networks
  - Path-based protection scheme
  - Link-based protection scheme
## Types of Fault-Recovery Mechanisms

- **Protection**
  - Backup resources (routes and wavelengths) pre-computed and reserved in advance (before a failure occurs)
  - Faster recovery time

- **Restoration**
  - Routes and wavelengths discovered dynamically upon detection of a failure
  - Resources allocation based current network state info
  - More resource efficient
  - Slower recovery time

### Different protection and restoration schemes

<table>
<thead>
<tr>
<th>Protection/Restoration Schemes</th>
<th>Protection</th>
<th>Restoration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ring</td>
<td>Link</td>
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<td></td>
<td>Mesh</td>
<td>Path</td>
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<td>Path</td>
<td>Protection</td>
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![Diagram showing different protection and restoration schemes]
Types of Fault-Recovery Mechanisms

- Protection
  - Ring protection
    - Automatic protection switching (APS)
    - Self-healing rings (SHR)
    - Pre-configured cycles (p-cycle)
  - Mesh protection

- Path protection
  - Two link (node) disjoint paths: primary (working) and backup (protection) path
  - Traffic rerouted through a link-disjoint backup route once a link failure occurs on working path
  - Usually, less resource required (using shorter routes)
  - Lower end-to-end propagation delay for the recovered route

- Link protection
  - Do not change the entire end-to-end path
  - Traffic rerouted only around the failed link
  - Faster recovery time since no end-to-end signaling required
Mesh Protection

- Control: Centralized or Distributed
- Route Calculation: Preplanned or Dynamic
- Type of Alternate Routing: Line or Path

Types of Fault-Recovery Mechanisms

- Path Protection
  - Two link (node) disjoint paths: primary (working) and backup (protection) path
  - Traffic rerouted through a link-disjoint backup route once a link failure occurs on working path
  - Backup path pre-reserved or pre-set up
  - Backup paths of different connections may or may not share common wavelengths on common links (details later)
  - Usually, less resource required (using shorter routes)
  - Lower end-to-end propagation delay for the recovered route
### Types of Fault-Recovery Mechanisms

- **Dedicated Path Protection**
  - Do not allow sharing among backup paths (resources)
  - Backup paths pre-configured
  - No switch configuration necessary along the backup path when a failure occurs
  - Fast recovery time
  - Resources not efficiently utilized (100% redundancy)

- **Shared Path Protection**
  - Allow sharing among backup paths subject to certain constraints
    - Primary paths link disjoint $\rightarrow$ backup paths may share common link and wavelength
  - Backup paths configured when a failure occurs since backup paths may be shared; cannot commit resources to a particular primary in advance
  - Slower recovery time
  - Resources utilization much better
  - More signaling required to recover from the failure
Types of Fault-Recovery Mechanisms

- **Link Protection**
  - a light-path set up on a primary path
  - For each link on the primary path, a backup loop is reserved around the link
  - No wavelength conversion → use same wavelength on backup loop
  - Wavelength conversion → may different one on backup loop
  - No sharing – dedicated-link protection
    - Wavelength used on backup loop dedicated to specific link to be protected
  - Shared-link protection
  - Note, different connections on the same link might have different backup loops for that link

Mesh Protection

- Control: Centralized or Distributed
- Route Calculation: Preplanned or Dynamic
- Type of Alternate Routing: Line or Path
Protection Problems in WDM Networks

- **Static traffic pattern**
  - Connection requests known all at once
  - RWA problem must be solved for each connection request – primary path and backup path
  - Subject to # of wavelengths on each link, # of transmitters and receivers, available
  - Wavelength continuity if no conversion
  - Minimize total # of wavelength-links
  - Or to maximize the carried load

- **Dynamic traffic**
  - Minimize overall call-blocking probability
  - Achieve small end-to-end propagation delays of connections which are set up

ILP Formulations of Protection Schemes

- **General Problem Statement**
- **Given**
  - a physical topology G=(V,E),
  - the # of wavelengths on each fiber,
  - a static traffic demand matrix,
  - **Route** each connection request on the physical topology according to the protection scheme used
  - **Assign a wavelength** to each path (primary & backup) such that
    - Total network cost is minimized or
    - The network throughput is maximized
Notations

- $N$: # of nodes in the network
- $E$: # of links in the network
- $W$: # of wavelengths on each link
- $\text{Links} = \{< i, j >\}$: the set of unidirectional links in the network
- $\Lambda_{N \times N} = \{\text{dem}_{i,j}\}$: traffic demand matrix
  - # of lightpaths requests between node pair $(i, j)$

Notations

- $F_{i,j,s,d,w}$:
  - 1: if wavelength $w$ on link $i \rightarrow j$ is used by some primary path between node pair $(s, d)$
  - 0: otherwise
- $S_{p,q,s,d,w}$:
  - 1: if wavelength $w$ on link $p \rightarrow q$ is used by some protection path between node pair $(s, d)$
  - 0: otherwise
- $\delta_{p,q,i,j,s,d,w}$:
  - 1: if wavelength $w$ on link $p \rightarrow q$ is used by some protection path between node pair $(s, d)$ when link $i \rightarrow j$ fails
  - 0: otherwise
- $m_{p,q,w}$:
  - 1: if wavelength $w$ on link $p \rightarrow q$ is used by some protection path
  - 0: otherwise
ILP1: Dedicated-Path Protection (no wavelength conversion)

- Idea
  - Route $2 \times \text{dem}_{s,d}$ light-paths between node pair $(s, d)$ since both primary and protection paths carry traffic
  - No differentiation between primary and protection paths
  - Link disjointness must be ensured

Objective: Minimize the total number of wavelength-links:

\[
\text{Minimize } \sum_{1 \leq s, d \leq N} \sum_{w=1}^{W} \sum_{\langle i, j \rangle \in \text{Links}} F_{i,j}^{s,d,w} \quad (4.1)
\]

Subject to $(1 \leq s, d \leq N, 1 \leq w \leq W$ if not specified):

Demand between each node pair $(s, d)$ is satisfied on primary paths:

\[
2 \times \text{dem}_{s,d} = \sum_{w=1}^{W} \sum_{\langle i, s, i', d \rangle i' \in \text{Links}} F_{i,s}^{s,d,w} \quad (4.2)
\]

\[
2 \times \text{dem}_{s,d} = \sum_{w=1}^{W} \sum_{\langle i, t, d \rangle \in \text{Links}} F_{i,d}^{s,d,w} \quad (4.3)
\]

\[
F_{i,s}^{s,d,w} = 0 \quad \forall \langle i, s, i' \rangle \in \text{Links} \quad (4.4)
\]

\[
F_{d,e}^{s,d,w} = 0 \quad \forall \langle d, e \rangle \in \text{Links} \quad (4.5)
\]

Flow conservation under wavelength-continuity constraint on primary paths:

\[
\sum_{\langle i, j \rangle \in \text{Links}} F_{i,j}^{s,d,w} - \sum_{\langle j, e \rangle \in \text{Links}} F_{j,e}^{s,d,w} = 0 \quad (4.6)
\]
ILP2: Shared-Path Protection (no wavelength conversion)

Objective: Minimize the total number of wavelength-links:

\[
\text{Minimize } \sum_{w=1}^{W} \sum_{(i,j) \in \text{Links}} (m_{i,j}^{w} + \sum_{1 \leq s,d \leq N} p_{i,j,d}^{s,w})
\]

Subject to (1 \leq s,d \leq N, 1 \leq w \leq W if not specified):

Demand between each node pair (s,d) is satisfied on primary paths:

\[
dem_{s,d} = \sum_{w=1}^{W} \sum_{(i,j) \in \text{Links}} p_{i,j,d}^{s,w}
\]

Flow conservation under wavelength-continuity constraint on primary paths:

\[
\sum_{i<j} p_{i,j,d}^{s,w} - \sum_{j<i} p_{j,i,d}^{s,w} = 0 \quad \forall s,d \in \text{Links}
\]

When a link \( i \rightarrow j \) fails, the number of lightpaths failed between source-destination pair (s, d) should not exceed the demand between them:

\[
\sum_{w=1}^{W} p_{i,j,d}^{s,w} \leq dem_{s,d} \quad \forall i,j \in \text{Links}
\]
Constraints on the number of rerouted lightpaths between node pair \((s, d)\) then link \(i \rightarrow j\) fails:

\[
\sum_{w=1}^{W} P_{i,j}^{s,d,w} = \sum_{w=1}^{W} \sum_{\forall e < i, j \in \text{Links}} \sum_{\forall p < e, d > \in \text{Links}} \delta_{p,e,i,j}^{s,d,w} \\
\forall < i, j > \in \text{Links} \tag{4.15}
\]

\[
\sum_{w=1}^{W} P_{i,j}^{s,d,w} = \sum_{w=1}^{W} \sum_{\forall p < s, d > \in \text{Links}} \sum_{\forall e < i, j \in \text{Links}} \delta_{p,e,i,j}^{s,d,w} \\
\forall < i, j > \in \text{Links} \tag{4.16}
\]

\[
\delta_{p,s,i,j}^{s,d,w} = 0 \quad \forall < p, s, i, j > \in \text{Links} \tag{4.17}
\]

\[
\delta_{d,e,i,j}^{s,d,w} = 0 \quad \forall < d, e, i, j > \in \text{Links} \tag{4.18}
\]

Flow conservation under wavelength-continuity constraint on protection paths:

\[
\sum_{\forall p < q, d > \in \text{Links}} \delta_{p,q,i,j}^{s,d,w} - \sum_{\forall e < q, r > \in \text{Links}} \delta_{q,r,i,j}^{s,d,w} = 0 \\
1 \leq q \neq s, d \leq N, < i, j > \in \text{Links} \tag{4.19}
\]

A primary path and its protection path must be link-disjoint:

\[
\delta_{i,j}^{s,d,w} = 0 \quad \forall < i, j > \in \text{Links} \tag{4.20}
\]

Two lightpaths protected by the same wavelength \(w\) on the same link \(p \rightarrow q\) cannot go through the same link \(i \rightarrow j\):

\[
\sum_{1 \leq s, d \leq N} \delta_{p,q,i,j}^{s,d,w} \leq 1 \quad \forall < p, q, i, j > \in \text{Links} \tag{4.21}
\]

Constraints indicating whether a wavelength \(w\) on link \(p \rightarrow q\) is used by some protection path:

\[
m_{p,q}^{w} \leq \sum_{1 \leq s, d \leq N} \sum_{\forall e < i, j > \in \text{Links}} \delta_{p,q,i,j}^{s,d,w} \\
\forall < p, q > \in \text{Links} \tag{4.22}
\]

\[
N \times N \times E \times m_{p,q}^{w} \geq \sum_{1 \leq s, d \leq N} \sum_{\forall e < i, j > \in \text{Links}} \delta_{p,q,i,j}^{s,d,w} \\
\forall < p, q > \in \text{Links} \tag{4.23}
\]

Wavelength \(w\) on link \(i \rightarrow j\) can only be utilized by either a primary path or protection paths:

\[
m_{p,q}^{w} + \sum_{1 \leq s, d \leq N} P_{i,j}^{s,d,w} \leq 1 \quad \forall < i, j > \in \text{Links} \tag{4.24}
\]
The above formulation performs per-failure-based protection, i.e., each failure scenario corresponds to different protection paths, which complicates connection control and management. We make it per-connection-based protection, i.e., each connection is assigned some protection resources no matter where the failure occurs, by adding the following constraints, (4.25) through (4.27).

Constraints indicating whether a wavelength \( w \) on link \( p \rightarrow q \) is used by some protection path between node pair \( (s, d) \):

\[
S_{p,q}^{s,d,u} \leq \sum_{\forall i,j \in \text{Links}} S_{p,q}^{i,j} \quad \forall <p,q> \in \text{Links} \tag{4.25}
\]

\[
E \times S_{p,q}^{s,d,u} \geq \sum_{\forall i,j \in \text{Links}} S_{p,q}^{i,j} \quad \forall <p,q> \in \text{Links} \tag{4.26}
\]

A primary path should not have more than one protection path:

\[
\sum_{\forall e <s,e> \in \text{Links}} F_{e}^{s,d,u} \geq \sum_{\forall e <s,e> \in \text{Links}} S_{e}^{s,d,u} \tag{4.27}
\]

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**ILP3: Shared-Link Protection (no wavelength conversion)**

Under shared-link protection scenario, any link \( i \rightarrow j \) of some primary path has a protection loop from node \( i \) to \( j \), which must be on the same wavelength as the wavelength of path \( p \). We extend ILP2 to shared-link protection by modifying (4.15) and (4.16) as follows.

\[
F_{i,j}^{s,d,u} = \sum_{\forall e <i,e> \in \text{Links}} S_{e}^{s,d,u} \quad \forall 1 \leq w \leq W, <i,j> \in \text{Links} \tag{4.28}
\]

\[
F_{i,j}^{s,d,u} = \sum_{\forall p <i,p> \in \text{Links}} S_{p}^{s,d,u} \quad \forall 1 \leq w \leq W, <i,j> \in \text{Links} \tag{4.29}
\]

Equations (4.25) through (4.27) become redundant in this case. The rest constraints are the same as in ILP2.
Extension to Wavelength Convertible Networks

When wavelength-continuity constraint is the case, flow conservation constraints, as in (4.14), (4.19), (4.28), and (4.29), must be held on a per-wavelength axis. We relax the per-wavelength-based flow conservation constraints to accommodate wavelength-convertible capability. Note that, in dedicated-path protection, the objective, number of wavelength-links, remains the same regardless whether or not the network is wavelength convertible.

1.2.3.1 ILP4: Shared-Path Protection

We extend ILP1 to accommodate wavelength conversion capability by relaxing wavelength-continuity constraints in (4.14) and (4.19) as follows.

Flow conservation on primary paths:

$$
W \sum_{w=1}^{W} \sum_{\forall i<j, i,j \in \text{Links}} F_{ij}^{w,d} - \sum_{w=1}^{W} \sum_{\forall i<j, i,j \in \text{Links}} F_{ij}^{w,d} = 0 \\
1 \leq j \neq s, d \leq N
$$

(4.30)

Flow conservation on protection paths:

$$
W \sum_{w=1}^{W} \sum_{\forall p,q, p,q \in \text{Links}} \xi_{p,q,ij}^{s,d,w} - \sum_{w=1}^{W} \sum_{\forall q, p, q \in \text{Links}} \xi_{q,p,ij}^{s,d,w} = 0 \\
1 \leq q \neq s, d \leq N, <i,j> \in \text{Links}
$$

(4.31)

ILP5: Shared-Link Protection

4.2.3.2 ILP5: Shared-Link Protection

This case can be easily derived from ILP2. Besides the same changes as we made in previous section, we relax the wavelength-continuity constraints in (4.28) and (4.29) as follows.

$$
W \sum_{w=1}^{W} F_{ij}^{s,d,w} = \sum_{w=1}^{W} \sum_{\forall e: <i,e> \in \text{Links}} \xi_{i,e,ij}^{s,d,w} \\
\forall 1 \leq w \leq W, <i,j> \in \text{Links}
$$

(4.32)

$$
W \sum_{w=1}^{W} F_{ij}^{s,d,w} = \sum_{w=1}^{W} \sum_{\forall p: <p,j> \in \text{Links}} \xi_{p,j,ij}^{s,d,w} \\
\forall 1 \leq w \leq W, <i,j> \in \text{Links}
$$

(4.33)
**Dedicated-path protection – Heuristic Algorithms**

- Joint-path-selection (primary and backup) schemes have better performance compared to separate-path-selection schemes in terms of the amount of network resources required.
- Use Suurballe’s algorithm to compute two link-disjoint paths between \((s, d)\) simultaneously.
- **Suurballe’s algorithm**: Given a graph \(G=(V, E)\), find a pair of edge-disjoint paths from \(v\) to \(t\) such that the total edge cost of the two paths is minimal among all such path pairs.

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**Dedicated-path protection – Heuristic Algorithms**

- Remove links that do not have free wavelengths.
- Apply Suurballe’s algorithm to find a pair of paths.
- Choose the shorter path as the primary path and the longer path as the backup.
- Assign a wavelength using First-Fit to each path.
**Shared-Path Protection - Heuristic 1**

- Use Suurballe’s algorithm to generate two routes
- Assign wavelengths while trying to share the wavelengths on the backup paths as much as possible
- Does not perform well in backup path sharing since routing does not consider wavelength info

**Shared-Path Protection – Heuristic 2**

- **Primary path**: apply a standard shortest-path algorithm to compute
- If the shortest path is selected as the primary and a link-disjoint backup path cannot be found,
  - apply the Suurballe’s algorithm to compute a pair of routes and use the shorter one as the primary path
- **Otherwise Backup path**: use shortest-widest Bellman-Ford algorithm
  - Search for the shortest-widest path
  - The widest path is the path that has the largest # of wavelengths that can be re-used (shared)
  - If two such paths exist, the shorter one is selected
In a wavelength-convertible network, the “width” of a candidate backup path $p_b$ for a primary path $p_w$ is calculated by the following equations.

$$\text{width}(p_b, p_w) = \min_{l_b \in P_b} \text{width}(l_b, p_w)$$  \hspace{1cm} (4.34)

$$\text{width}(l_b, p_w) = \min_{l_w \in p_w} \text{width}(l_b, l_w)$$  \hspace{1cm} (4.35)

$$\text{width}(l_b, l_w) = 1 - \frac{h_{l_b}^{l_w}}{\max_{l} h_{l_b}^l}$$  \hspace{1cm} (4.36)

In the equations above, $l_b, l_w$ and $l$ are links. In Eqn. (4.36), $h_{l_b}^{l_w}$ is the number of wavelengths on link $l_b$ that can be used to protect link $l_w$, and $\max_{l} h_{l_b}^l$ is the total number of wavelengths on link $l_b$ that are reserved for protection. Note that $h_{l_b}^{l_w} \leq \max_{l} h_{l_b}^l$. Therefore $0 \leq \text{width}(l_b, l_w) \leq 1$. By Eqns. (4.34) and (4.35), all width values are between 0 and 1.

If $h_{l_b}^{l_w} = \max_{l} h_{l_b}^l$, then $\text{width}(l_b, l_w) = 0$, and a new wavelength must be used if $l_b$ is selected on the backup path for the primary path that contains link $l_w$. The widest path is the path that has the largest number of wavelengths that can be re-used (shared). If two such paths exist, the shorter one will be selected.

**Shared-Path Protection -- Heuristic 2 cont’d**

In a wavelength-continuous network, we extend the definition of “width” of a path to the “width” of a path on a particular wavelength. The “width” of a candidate backup path $p_b$ on wavelength $\lambda^*$ for a primary path $p_w$ is calculated by the following equations.

$$\text{width}(p_b, \lambda^*, p_w) = \min_{l_b \in P_b} \text{width}(l_b, \lambda^*, p_w)$$  \hspace{1cm} (4.37)

$$\text{width}(l_b, \lambda^*, p_w) = \min_{l_w \in p_w} \text{width}(l_b, \lambda^*, l_w)$$  \hspace{1cm} (4.38)

$$\text{width}(l_b, \lambda^*, l_w) = \begin{cases} 0 & \text{if } \lambda^* \text{ on } l_b \text{ is protecting } l_w \\ 1 & \text{otherwise} \end{cases}$$  \hspace{1cm} (4.39)
Shared-Link Protection – Heuristic

- Primary path – apply a standard shortest-path algorithm to compute
- For each link in the primary path
  - Search a shortest-widest backup path (loop) between two end nodes

cont’d

searched between the two end nodes. If the network is wavelength-convertible, Eqn. (4.36) is applied to compute the width of a protecting link with respect to the protected link. The following equation shows how to compute the width of a path $p_b$ that protects link $l_w$:

$$width(p_b, l_w) = \min_{l_b \in p_b} width(l_b, l_w)$$  \hspace{1cm} (4.40)

If the network is wavelength-continuous, the same wavelength used on the primary path will be used on the backup paths. Therefore only one wavelength needs to be examined. Assume wavelength $\lambda^*$ is used on the primary path. Eqn. (4.39) is used to compute the width of a protecting link on wavelength $\lambda^*$ with respect to the protected link. The following equation shows how to compute the width of a path $p_b$ that protects link $l_w$ on wavelength $\lambda^*$:

$$width(p_b, \lambda^*, l_w) = \min_{l_b \in p_b} width(l_b, \lambda^*, l_w)$$  \hspace{1cm} (4.41)
Pre-configured Cycle (p-cycle)

A p-cycle in a network

On cycle link failure

Straddling link failure

Path 1

Path 2

Pre-configured Cycle (p-cycle)

Restoration using p-Cycles

A. Form the spare capacity into a particular set of pre-connected cycles!

A span on the cycle fails - 1 Restoration Path, BLSR-like

A span off the p-cycle fails - 2 Restoration Paths, Mesh-like
Protection Switching and Inter-node Signaling

Nodes neighboring the failure react

No protection path signaling needed (Preconfiguration)

Fast protection switching

Link Protection vs. $p$-cycles in WDM Networks

- Link protection (dedicated, without inter-node signaling):
  - No capacity sharing

- $p$-cycles:
  - Capacity sharing
### p-cycle Based Protection

- A pre-configured cycle (p-cycle) based protection technique combines the benefits of both
  - the traditional ring-based and
  - path-based approaches
  - it can achieve *ring-like recovery speed* while retaining the desired *capacity efficiency of path-based protection* approaches.

### p-cycle Based Protection Design Method

**Step 1:** Find set of elementary cycles of the network graph

**Step 2:** For each cycle, determine $x_{ij}$: the no. of restoration paths that cycle $i$ contributes for failure $j$.

**Step 3:** Integer Program:

- **Objective:** *minimize* total cost of spare capacity.

- **Subject to:**
  1. All working links on each span have (simultaneously feasible) access to one or more p-cycles.
  2. All p-cycles placed are feasible within the span spare capacities assigned.
Optimal $p$-cycle network design

- $S$: number of network spans (known constant, input)
- $s_j$: number of spare links on span $j$ (variable)
- $w_j$: number of working links on span $j$ (known, input)
- $n_i$: number of copies of cycle $i$ (variable to be determined)
- $x_{ij}$: number of restoration paths cycle $i$ provides for failed span $j$ (0, 1, 2, input)
- $p_{ij}$: number of spare links required on span $j$ for an instance of cycle $i$ (0 or 1, input)
  - 1 if cycle $i$ passes through span $j$
- $c_j$: the cost of a unit capacity on span $j$ (known constant, input)

\[
\text{minimize } \sum_{j=1}^{S} c_j s_j \quad \text{(EQ 1)}
\]

Subject to:

\[
s_j = \sum_{i=1}^{\vert P \vert} p_{i,j} \cdot n_i \quad \forall j = 1, 2, \ldots, S \quad \text{(EQ 2)}
\]

\[
w_j \leq \sum_{i=1}^{\vert P \vert} x_{i,j} \cdot n_i \quad \forall j = 1, 2, \ldots, S \quad \text{(EQ 3)}
\]

\[
n_i \geq 0 \quad \forall i = 1, 2, \ldots, \vert P \vert \quad \text{(EQ 4)}
\]
### Optimal $p$-cycle network design result

<table>
<thead>
<tr>
<th>Net</th>
<th>Excess Sparing</th>
<th># of unit-capacity $p$-cycles formed</th>
<th># of Unique cycles used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net1</td>
<td>9.09 %</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Net2</td>
<td>3.07 %</td>
<td>88</td>
<td>10</td>
</tr>
<tr>
<td>Net3</td>
<td>0.0 %</td>
<td>250</td>
<td>10</td>
</tr>
<tr>
<td>Net4</td>
<td>2.38 %</td>
<td>2237</td>
<td>27</td>
</tr>
<tr>
<td>Net5</td>
<td>0.0 %</td>
<td>161</td>
<td>39</td>
</tr>
</tbody>
</table>