Bridging the Ring-Mesh Dichotomy with \( p \)-cycles:

*Ring-like speed with mesh-like capacity*

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Overview

- Background & Motivation
- Concept and properties of p-cycles
- Optimal p-cycle capacity design
- ADM-like ‘capacity slice’ nodal device
- Self-organized p-cycle formation
- Fast IP layer span restoration
- IP Layer node restoration
- “Controlled over-subscription” IP layer design
Background and Motivation

<table>
<thead>
<tr>
<th>“Ring”</th>
<th>“Mesh”</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A.</strong> 50 - 60 msec restoration time</td>
<td><strong>E.</strong> 100 msec - 2 sec. typical</td>
</tr>
<tr>
<td>B. complex capacity design &amp; network planning</td>
<td><strong>F.</strong> <em>simple, exact spare capacity planning</em></td>
</tr>
<tr>
<td>C. high total capacity for service provided</td>
<td><strong>G.</strong> <em>well under 100% spare capacity</em></td>
</tr>
<tr>
<td><strong>D.</strong> <em>simple, low-cost ADMs</em></td>
<td><strong>H.</strong> Relatively expensive DCS nodes</td>
</tr>
</tbody>
</table>

- Wouldn’t it be good to have A., D., F. and G. together!?
Q. How could you ever have the spare capacity of a mesh network completely pre-connected in advance of any failure?
Restoration using $p$-Cycles

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

A $p$-cycle

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

A span off the $p$-cycle fails - 2 Restoration Paths, Mesh-like
Optimal Spare Capacity Design for $p$-Cycle Restoration:

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

- **Step 2:** For each cycle, determine $x_{i,j}$: the no. of restoration paths that cycle $i$ contributes for failure $j$. $x_{i,j} \in \{0, 1, 2\}$

- **Step 3:** **Integer Program to select optimal $p$-cycle set:**
  
  **Objective:** minimize: total cost of spare capacity.

  **Subject to:**
  
  1. **Restorability:** All working links on each span have (simultaneously feasible) access to one or more $p$-cycles.
  
  2. **Spare Capacity:** All $p$-cycles placed are feasible within the span spare capacities assigned.
Network #2

- Net #1 with reduced spans
- same demand matrix
- 11 nodes
- 20 spans
- $D = 3.6$
Network #3

- Net #1 augmented
- same demand matrix
- 15 nodes
- 28 spans
- $\overline{D} = 3.7$
Network #4

- European Cities from DRCN '98
- gravity demand model
- 19 nodes
- 39 spans
- $\bar{D} = 4.1$
Optimal Spare Capacity Design: Results

- “Excess Sparing” = Spare Capacity compared to Optimal Span-Restorable Mesh:

<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>
### Comparing the *p*-Cycle Concept to Rings

<table>
<thead>
<tr>
<th>Attribute</th>
<th><em>p</em>-cycles</th>
<th>SONET rings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modularity</td>
<td>One spare capacity signal unit</td>
<td>OC-n modularity</td>
</tr>
<tr>
<td>Protection Yield</td>
<td>Up to two paths per <em>p</em>-cycle</td>
<td>One restoration path per use</td>
</tr>
<tr>
<td>Protection Flexibility</td>
<td><em>p</em>-cycles contribute to restoration of on-cycle <em>and</em> “straddling” failures</td>
<td>Rings only protect spans on the same ring</td>
</tr>
<tr>
<td>Routing and provision of working paths</td>
<td>Proceeds without regard to structures formed in the sparing layer</td>
<td>Working path routing must conform to ring systems and limited inter-ring transfer points</td>
</tr>
<tr>
<td>Total Network Redundancy</td>
<td>~ span restorable mesh (&lt; 100%)</td>
<td>Over 100% investment in spare capacity. Up to ~300%</td>
</tr>
</tbody>
</table>
Comparing $P$-Cycle Concept to Rings

BLSR or UPSR ($w=9 : s=9$)  $p$-Cycle ($w=19 : s=9$)
ADM - like “Capacity slice” nodal device for p-cycle networking

Nodal Redundancy = \( \frac{\text{spare}}{\text{working}} \) = \( \frac{1}{k+1} \)

e.g. if \( k = 3 \) → 25%

(patents pending)
Self-organizing formation of p-cycles
(DCPC Protocol)

**GOAL:** Have the network determine, and continually adapt, its set of p-cycles for maximum failure-readiness

- Based on modified Tandem node rules from Selfhealing Network (SHN) protocol
- Operates autonomously, continuously, in background, on spare links only.
- A "Pro-Active", *non- real time process* - Somewhat like “distributed pre-planning” use of a restoration algorithm but...
- Determines not only what to do upon failure, but also pre-operates the cross-connections between spares in advance.
- Upon failure, the only real-time action is to make pre-armed traffic substitution connections
- No real time signalling requirement if *p*-cycles kept under “audit” while in storage
DCPC Tandem Node Broadcast Rules

- Incoming statelets rebroadcast to the largest extent possible
- subject to:  - Competition based on incoming “scores”
  - Re-Broadcast “direction rules”

![Diagram of tandem node broadcast rules]

- Cycler Node
- Tandem Node
- Existing Relationship Trail
- Permitted
- Invalid

“home”
“been there”
“new nodes”

Nodes A, B, C, D, E, F, G

Existing relationships and permitted trails are depicted in the diagram.
Tandem Node Competition Rules

- Score is determined by:

\[
\text{Score} = \frac{\text{Useful Restoration Paths}}{\text{Links used}}
\]

Re-Broadcast Competition

- 4 Incoming Statelets
- 3 Broadcast Families
- Statelet Ranking by Score:

\[s1 - s2 - s3 - s4\]
Tandem Node Evaluation of Statelet Score

Path evaluation for a Statelet broadcast Arriving at a Tandem Node

Statelet Broadcast Route: C-1-2-T

Case 1: No Paths
Failure of Span T-3

Case 2: 1 Paths
Failure of Span T-2

Case 3: 2 Paths
Failure of Span T-1

Case 4a: 2 paths
Broadcast to a Tandem
Failure of Span T-C

Case 4b: 1 paths
Broadcast to the Cycler
Failure of Span T-C
Tandem Node Formation of “Best” Cycles
How Path count is updated Incrementally for a Statelet Broadcast

- Highest score cycle emerges under Tandem node competition rules

- “Useful” paths \{C-1-2-3-4-C\} = 1 + 1 + (1+2+2) + 1 + 1 = 9
- links used = 5
- “score” = 9/5
DCPC Protocol: Performance

- **OPNET Modeler** Simulation experiments

- Tested in Stringent *Minimal-Capacity* Network Designs:

- **Results:**

<table>
<thead>
<tr>
<th>Network</th>
<th>$p$-cycle Restorability (%)</th>
<th>2-step Restorability (%)</th>
<th>With OC-n Modularity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net1</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Net2</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Net3</td>
<td>90.94</td>
<td>97.16</td>
<td>91.53 / 98.49</td>
</tr>
<tr>
<td>Net4</td>
<td>89.16</td>
<td>97.68</td>
<td>100</td>
</tr>
<tr>
<td>Net5</td>
<td>83.75</td>
<td>95.44</td>
<td>95 / 100</td>
</tr>
</tbody>
</table>
The Real-time phase of Restoration with $p$-cycles

$p$-cycle 1: restores 1 Path

$p$-cycle 2: restores 2 Paths

$p$-cycle 3: restores 2 Paths

$p$-cycle 4: not used

Total Restoration Paths = $1 + 2 + 2 + 0 = 5$

5 Spans Fail
Concluding Discussion: Significance and Benefits

- *The p-cycle concept offers the prospect of ring-like speed, with mesh-like efficiency.*

- The key to the mesh like efficiency: *p-cycles protect straddling failures as well as on-span failures.*

- *p-cycles leave the working capacity free to be routed without constraints from protection structures (unlike rings)*

- *p-cycles can be centrally computed or self-organized by the network (DCPC Protocol): Proactive in two senses*
  - Computation of restoration *planning* is completed *Prior to Failure*
  - Restoration *Path-formation* is *also* completed *Prior to Failure*

- *p-cycles may be kept under constant readiness testing. Each node then knows (a) restoration action, (b) restoration path status, and (c) restoration level to expect, all in advance.*

- *Possible applications in WDM optical networking*
Internet Protocol (IP) Restoration

- IP Networks are already “Restorable”
  - Restoration occurs when the Routing protocol updates the Routing Tables
  - This update can take a Minute or more - Packets are lost until this happens

- Speed-up of IP Restoration is needed
IP Router Restoration using $p$-Cycles

- IP $p$-Cycles are formed as Virtual Circuits/Protection Structures which can redirect IP Packets around Failures
  - Plain IP is Connectionless but $p$-Cycles can be realized with MPLS, IP Tunneling/Static Routes
Router Restoration using "Node-Encircling" p-Cycles

- **Key concept:** Node Encircling p-Cycles. Each Node has a p-Cycle dedicated to its failure.
- For each Node, a p-Cycle is chosen which includes all logically "Adjacent" Nodes but not the Protected Node.
Router Restoration using p-Cycles: p-Cycle Examples

Simple

Non-Simple (Segment)

Non-Simple (Figure “8”)
**p-Cycle Encapsulation**

- The p-cycle packet contains the IP packet and new fields:
  - The ID of the p-cycle on which the packet belongs
  - The original path cost of the pre-failure path for the IP packet
p-Cycle Routing

Router Processing of p-Cycle Packet arrival:

Destination  =  Destination Address of the Original IP Packet in the p-Cycle Packet’s Payload

**IF**  (a local Routing Table Entry for Destination exists) **AND**  
  (the Routing Entry’s Egress Port is Functioning) **AND**  
  (the Routing Entry’s Path Cost < p-Cycle Packet’s Original Path Cost)

**THEN**

Remove Original IP Packet from p-Cycle Packet and Route it Normally

**ELSE:**

Continue the Packet along the p-Cycle
p-Cycle Routing Example

Packet Routing (Pre-Failure)
Path Cost = 3 (3 hops)

Path Cost = 3 (3 hops)

But …
Failure

Routing through p-Cycle

Packet Routing (Post-Failure)

Routing
Normal Routing

But …

Path Cost = 3 (3 hops)
IP Span Restoration using p-Cycles

- A Span Failure only disrupts the Connection between a single Node pair
- Re-routing Mechanism is simpler than Node case
  - Need only re-route between a single node pair
- A p-Cycle is used to reroute packets between the node pair
Concluding Discussion

- **SONET / WDM Networks**
  - *The p-cycle concept offers the prospect of ring-like speed, with mesh-like efficiency.*
  - The key to the mesh like efficiency: *p-cycles protect straddling failures as well as on-span failures.*

- **Internet Protocol Networks**
  - p-Cycles are used as Virtual Protection Structures to protect packets while IP Routing Protocols restore a failure
  - p-Cycles can protect against both Node and Span failures in IP Networks