Motivation

- Customers have a range of availability requirements
  - Consumer Internet access (.93 - .95) ➔ customers happy
  - Most businesses subscribe to .999 or less type service
  - Emerging applications: Smart Grid, Emergency Communications, Telemedicine — need .99999 or greater end to end.
  - ONLY a SMALL Fraction of Users/Traffic need high levels of availability and are willing to PAY for it!
  - However high availability traffic derives the design ➔ free rider scenario

- Network Operators provide differentiated Quality of Resilience (QoR) classes
  - Categorize services into QoR classes (Bronze, Silver, Gold)
  - Each QoR class different levels of protection and routing
    - Gold: 1+1 dedicated path protection
    - Silver: Shared backup path protection
    - Bronze: No Protection
  - If not reliable enough — additional protection, redundant protection across layers
Highly Available Spine

• Spine Concept
  – High availability must begin at physical layer and work it’s way up
  – Spine: embed a higher availability subnetwork into the physical layer providing a basis for QoR
  – Highest class of QoR WP or BP routed on SPINE

Nodes, link interfaces and links on Spine have higher availability

Other links and nodes lower availability

Highly Available Spine

• How to provide availability differentiation for components on spine versus those off spine?
• Equipment differentiation
  – Vendors claim can get a range of availabilities by equipment arrangement/configuration and cost (e.g. hot standby line card, redundant fans, redundant backplane, etc) (.99 - .999997)
• Equipment Site differentiation
  – Situate Spine equipment to increase MTTF - longer back up power supplies, better heating/cooling, stronger outside cabinets, etc
  – Underground links versus above ground, etc.
• Reduce MTTR along Spine (5% - 25% in other industries)
  – Follow best practices and training procedures (NRIC, FCC)
  – Pre-position spare parts/equipment
  – Assign most experienced staff to OAM Spine portion of network
  – Ex. WDM OXC 99.994% → (99.9943% - 99.9955%)
**Spine Concept**

- Improve overall availability by making strong stronger in parallel systems
- Example
  - Let all the links have the same availability $a$
  - Spine in red
    
    spine links $a_{S} = a + \Delta$
    
    off spine links $a_{o} = a - \Delta$
    
    - $A_{S}$ average end to end flow availability
      - One hop working path, two hop backup path

    | Case | $A_{S}$ | Downtime (hours/year) |
    |------|---------|-----------------------|
    | $a = 0.9$, $\Delta = 0$ | 0.981 | 166.44 |
    | $a = 0.9$, $\Delta = 0.09$ | 0.99712 | 25.23756 |
    | $a = 0.9$, $\Delta = 0.099$ | 0.999701 | 2.61749 |


**Multi-layer Network Model**

- Two layer network: physical $G_{P} = (V_{P}, E_{P})$, logical $G_{L} = (V_{L}, E_{L})$
- Logical links $E_{L}$ are mapped to paths of physical links $E_{P}$.
- The spine, $G_{S}$ is defined as $V_{S} \subseteq V_{P}$ and $E_{S} \subseteq E_{P}$.
  - For full connectivity $\Rightarrow$ spine is min spanning tree (MST) i.e., $|E_{S}| = |V_{P}| - 1$.
- Demands, $D_{\phi}$, routed at the logical layer
Multi-layer Network Model

• Logical routing should isolate traffic of different QoR classes
  – Results in multiple logical networks, one for each class.

• class-1 ($\phi = 1$) requires high availability levels

• Flows are routed on logical links mapped to a fully disjoint working and backup path-pair in physical network, one of which is restricted to be on the spine.

Multi-layer Network Model

• class-2 ($\phi = 2$) has no strict availability requirements.
  • Flows of class-2 are routed freely on the network with no protection
Multi-Layer Design Problems

- Two optimization models developed
  - Model I: Duplicate logical links
    - Assume each class has the same set of logical links that are duplicated for exclusive use of each class.

- Model II: Partitioned logical network
  - Classes do not necessarily have identical logical networks.
  - Logical network is partitioned into two sub-networks, each network must be capable of carrying all demands of its class.

Multi-Layer Network Design

- Model I: Duplicate Logical Link model

\[
\begin{align*}
\text{minimize} & \quad \sum_{i \in E_L} \sum_{k \in C_L} \left( X_{ik}^{\text{in}} + Y_{ik}^{\text{in}} \right) \\
\text{subject to} & \quad \sum_{i \in E_L} \sum_{k \in C_L} \left( X_{ik}^{\text{in}} + Y_{ik}^{\text{in}} \right) = \sum_{i \in E_L} \sum_{k \in C_L} \left( X_{ik}^{\text{in}} + Y_{ik}^{\text{in}} \right) \\
& \quad \sum_{i \in E_P} \sum_{k \in C_L} \left( X_{ik}^{\text{in}} - Y_{ik}^{\text{in}} \right) = \sum_{i \in E_P} \sum_{k \in C_L} \left( X_{ik}^{\text{in}} - Y_{ik}^{\text{in}} \right) \\
& \quad \sum_{i \in E_P} \sum_{k \in C_L} \left( Y_{ik}^{\text{in}} - X_{ik}^{\text{in}} \right) = \sum_{i \in E_P} \sum_{k \in C_L} \left( Y_{ik}^{\text{in}} - X_{ik}^{\text{in}} \right) \\
& \quad \sum_{i \in E_P} \sum_{j \in L_P} \left( X_{ij}^{\text{in}} + Y_{ij}^{\text{in}} \right) \leq e_{ij} \\
& \quad \sum_{i \in E_L} \sum_{j \in L_L} \left( X_{ij}^{\text{in}} + Y_{ij}^{\text{in}} \right) \leq e_{ij} \\
& \quad \sum_{i \in E_L} \sum_{j \in L_L} \left( X_{ij}^{\text{in}} + Y_{ij}^{\text{in}} \right) \geq 0, \quad X_{ij}^{\text{in}} \geq 0, \quad Z_{ik}^{\text{in}} \geq 0
\end{align*}
\]

\text{OBJECTIVE}
Minimize total resources

\[
\begin{align*}
& \quad \sum_{i \in E_L} \sum_{k \in C_L} \left( X_{ik}^{\text{in}} + Y_{ik}^{\text{in}} \right) \\
& \quad \sum_{i \in E_P} \sum_{k \in C_L} \left( X_{ik}^{\text{in}} - Y_{ik}^{\text{in}} \right) = \sum_{i \in E_P} \sum_{k \in C_L} \left( X_{ik}^{\text{in}} - Y_{ik}^{\text{in}} \right) \\
& \quad \sum_{i \in E_P} \sum_{k \in C_L} \left( Y_{ik}^{\text{in}} - X_{ik}^{\text{in}} \right) = \sum_{i \in E_P} \sum_{k \in C_L} \left( Y_{ik}^{\text{in}} - X_{ik}^{\text{in}} \right) \\
& \quad \sum_{i \in E_P} \sum_{j \in L_P} \left( X_{ij}^{\text{in}} + Y_{ij}^{\text{in}} \right) \leq e_{ij} \\
& \quad \sum_{i \in E_L} \sum_{j \in L_L} \left( X_{ij}^{\text{in}} + Y_{ij}^{\text{in}} \right) \leq e_{ij} \\
& \quad \sum_{i \in E_L} \sum_{j \in L_L} \left( X_{ij}^{\text{in}} + Y_{ij}^{\text{in}} \right) \geq 0, \quad X_{ij}^{\text{in}} \geq 0, \quad Z_{ik}^{\text{in}} \geq 0
\end{align*}
\]

\text{Minimize total resources}
Multi-Layer Network Design

- Model II: Partitioned Logical Link model
- Modify Model I by adding the constraints below
  \[ ILP \text{ problem} \ - \text{problems solved in CPLEX} \]

\[ \begin{align*}
    \sum_{\text{max}} Z_{sl}^{\text{cl}} - M \xi_{st} & \leq 0, \quad \forall (s, t) \in E_L, \phi = 1 \\
    \sum_{\text{max}} Z_{sl}^{\text{cl}} - M(1 - \xi_{st}) & \leq 0, \quad \forall (s, t) \in E_L, \phi = 2 \\
    \xi_{st} & \in (0, 1) \text{ is binary}
\end{align*} \]

Numerical Results

- Evaluate Multi-Layer Network Design Models
- Consider Polska network as physical network: 12 nodes – 18 links
- Logical layer
  - generate a number of \( k \)-regular random graphs using \( k = 3, 4, 5, 6, \) and 7.
  - random, or random with a preselected set of links mapped to spine

\[ \Delta \] = max average WP-BP disjoint path-pair availability
\[ S_2 \] = maximizes the average WP path availability on the spine.
\[ S_1 \] = a compromise solution
Numerical Results

- For each spine, we ran 14 scenarios
  - Duplicate logical network: 6 scenarios
  - Partitioned logical network: 8 scenarios
  - Each scenario repeated 7 times – results averaged

- Full mesh of upper layer flows with single unit demand for each class ($d^{mn}_{\phi} = 1$; for all $mn$) 50/50 traffic split

- Averaged results compared in terms of
  - resource use: amount of reserved physical capacity required to realize the logical links
  - logical link downtime per class
  - end-to-end flow downtime per class

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**Numerical Results**

- Availability/Downtime Logical Link results:
  - Links on the spine $a_s = .999$, links off spine $a_O = .99$
  - Large difference between class 1 and 2!
  - Slight difference in class 1 results for spine – larger impact on class 2
  - Preselection of logical links to spine improves class 1

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**Table:**

<table>
<thead>
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<th>Scenario</th>
<th>Problem type</th>
<th>regular graph degree</th>
<th>total no. of logical links</th>
<th>prescheduled logical links</th>
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Numerical Results

- Availability/Downtime Logical End-to-End Flows results:
  - Links on the spine $a_s = .999$, links off spine $a_o = .99$
  - Large difference between class 1 and 2!

<table>
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<th>Scenario</th>
<th>Problem type</th>
<th>links on spine</th>
<th>total no. of logical links</th>
<th>Average flow expected downtime Class 1 (hour)</th>
<th>Average flow expected downtime Class 2 (hour)</th>
<th>Maximum expected flow downtime Class 1 (hour)</th>
<th>Maximum expected flow downtime Class 2 (hour)</th>
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</table>

Slight differences in total resource efficiency across the spines.

Some what larger differences on class-1 WP depends heavily on the spine topology.

Preselected logical Links scenarios requires less resources - affected by the logical topology layout.
Numerical Results

- Results compared against no-spine baseline model
- Downtime
  - Class-2
    - Links/flows have same results
  - Class-1
    - Downtimes for class-1 10X orders more than the spine model.
- Resources
  - Spine approach can use non-shortest path routing ➔ more resources
  - Percentage of increase in resources when using the spine can be as low as 0.8% depending on spine and logical topology

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average Class-1 logical link downtime (hr/yr)</th>
<th>Average Class-1 flow expected downtime (hr/yr)</th>
<th>Maximum Class-1 logical link downtime (hr/yr)</th>
<th>Maximum Class-1 flow expected downtime (hr/yr)</th>
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<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average total resources</th>
<th>% Percentage of increase in total resource usage when using the spine</th>
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Numerical Results

- Resources
  - Additional resources of spine approach depends on ratio of highest QoR class to lower classes
  - Would expect highest QoR class traffic to be small percentage of traffic
  - Vary ratio of QoR1/QoR2
  - Decrease in additional spine resources

<table>
<thead>
<tr>
<th># scenario</th>
<th>Traffic rate</th>
<th>Class-1 demand</th>
<th>Class-2 demand</th>
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Summary

• Quality of Resilience Classes in multi-layer networks
  – Deploy high available spine to create heterogeneous availability subnetworks at the physical layer to lay a basis for differentiation.
    • Spine created by component MTTF and MTTR differentiation
  – Cross layer mapping schemes to transfer differentiation capability to upper layers providing multiple logical networks with diverse QoR

• Two Network Design Models Developed
  – Duplicate links, Partitioned Networks
  – Numerical results show it widens the range of availability levels compared to existing techniques.
  – Effectiveness depends on
    • the layout of the logical layer
    • the spine used
    • the percentage of highest QoR class traffic

• Future work: restoration at top layer, optimum spine selection for multilayer network