A NETWORK PROTECTION DESIGN MODEL AND A STUDY OF THREE-LAYER NETWORKS WITH IP/MPLS, OTN, AND DWDM

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Main Contributions and Problem Considered

- IP/MPLS over OTN over DWDM network protection.
- Three-layer modeling.
- OTN sublayer technological constraints explicitly considered.
- Layers’ modularity.
- Comprehensive study.
  - Varying layers’ costs and parameters to understand the correlation effects between the layers.
Presentation Outline

- OTN overview.
- Motivation and related work.
- Network protection overview.
  - Single-layer vs. multi-layer survivability.
- Paper Contributions.
- Design Model:
  - Approach.
  - Protection mechanisms.
  - Notations, constraints, and objective.
- Solution Approach.
- Study Environment.
- Results.
What is OTN?

- **Optical Transport Network.**
- A new-generation transmission layer technology.
- Large-granule broadband service transmissions.
- A “digital wrapper” layer.
- Efficient multiplexing and switching of high-bandwidth signals.
OTN Signals

- Optical Data Unit (ODU) layer.
- $\text{ODU}_k$ Multiplexing.
- $\text{ODU}_k \rightarrow U_k$

<table>
<thead>
<tr>
<th>$U_k$ Signal</th>
<th>Bit-Rate (Gbps)</th>
<th>Max. $U_k$s in a wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_0$</td>
<td>1.25</td>
<td>80</td>
</tr>
<tr>
<td>$U_1$</td>
<td>2.5</td>
<td>40</td>
</tr>
<tr>
<td>$U_2$</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>$U_3$</td>
<td>40</td>
<td>2</td>
</tr>
<tr>
<td>$U_4$</td>
<td>100</td>
<td>1</td>
</tr>
</tbody>
</table>
Problems with 2-layer architectures.

- IP/MPLS over point-to-point WDM.
  - EOE conversion.
  - Routers’ capacity heavily consumed by forwarding services.
  - More time to detect failure at WDM.
- IP/MPLS over WDM (with OXCs).
  - No explicit consideration for the technological constraints of the middle layer.

Our approach:

- Three-Layer IP/MPLS over OTN over WDM.
  - Separates the logical from the physical topologies.
  - Explicitly consider the OTN layer.
Related Work I

- **OTN:**
  - G.709 Hierarchy Optical Transport Core Network Design, Requirements and Challenges. [Nee Ben Gee(2009)]
  - Interworking of IP and OTN networks – making IP over OTN a reality. [Nowell(2009)]
  - Optical transport networks: From all-optical to digital. [Puglia(2009)]
Multilayer Networks:
- IP over SONET. [J. Manchester (1998)]
- Cost comparison of IP/WDM vs. IP/OTN for European backbone networks. [I. Tsirilakis (2005)]
- Survivable MPLS Over Optical Transport Networks: Cost and Resource Usage Analysis. [W. Bigos (2007)]
- Dynamic LSP Routing in IP/MPLS over WDM Networks. [S. Koo (2006)]
- Two Design Problems for the IP/MLPS over WDM Networks. [E. Kubilinskas (2005)]

- The OTN layer has not been explicitly considered.
- No work found on Three-Layer networks in which the technological constraints of the middle sub-layer are explicitly considered.
### Overview: Single Layer Protection

#### At what layer?

<table>
<thead>
<tr>
<th></th>
<th>Upper layer</th>
<th>Lower layer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pros</strong></td>
<td>Network can recover from any failure.</td>
<td>Faster than recovery at the upper layer.</td>
</tr>
<tr>
<td></td>
<td>Upper layer often carries differentiated services with different QoS</td>
<td>Requires considerably fewer actions due to the coarser granularity of the</td>
</tr>
<tr>
<td></td>
<td>requirements, it is generally easier to offer differentiated survivability at this layer.</td>
<td>lower layer.</td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td>Recovery time is usually higher.</td>
<td>Some failures (e.g. an IP router failure) can not be handled by the lower layer.</td>
</tr>
<tr>
<td></td>
<td>In case of failure at the lower layer, there could be a huge amount of upper layer traffic affected by the failure in which case a great amount of recovery process at the upper layer is required.</td>
<td></td>
</tr>
</tbody>
</table>
How to design a survivable multilayer network with two goals in mind:

1. to maximize the network protection and,
2. to reduce the cost of the network recourses.

Issues:

- Spare capacity design.
  - Redundant protection.
  - Spare capacity left unprotected.
- Protection method to use.
  - Depends on the requirements of the ISP and whether a method is technologically meaningful.
A three-layer protection design where only the normal flow of each layer is 100% protected.

Appropriate protection method at each layer.

A design based on the separation of the capacity components of each layer.

Phase-based heuristic approach.

Study and Results.
A Capacity component of an upper layer becomes a demand on its neighboring lower layer.
Protection Mechanisms

- **IP/MPLS:**
  - 1:1 protection.
  - Hot standby path protection.

- **OTN:**
  - Link restoration on a single path.

- **DWDM:**
  - 1+1 protection.
  - Fixed backup path.
Indices:
- \( d = 1, 2, ..., D \) demands between source-destination pairs of the IP/MPLS layer.
- \( p = 1, 2, ..., P_d \) candidate pair of (primary, protection) paths (\( P_{dp}, R_{dp} \)) for realizing demand \( d \).
- \( e = 1, 2, ..., E \) links of the IP/MPLS layer.
- \( q = 1, 2, ..., Q_e \) candidate paths of OTN layer for realizing capacity of link \( e \).
- \( g, l = 1, 2, ..., G \) links of the OTN layer.
- \( r = 1, 2, ..., R_g \) candidate restoration paths for link \( g \).
- \( z = 1, 2, ..., Z_g \) candidate pair of (primary, protection) paths (\( Z_g, A_g \)) of DWDM layer for realizing capacity of link \( g \).
- \( v = 1, 2, ..., V_g \) candidate paths of DWDM layer for realizing capacity of link \( g \).
- \( f = 1, 2, ..., F \) links of the DWDM layer.
- \( k = 0, 1, 2, 3, 4 \) modular interfaces of OTN link \( g \).

Constants:
- \( h_d \): Volume of demand \( d \).
- \( \delta_{edp} = 1 \) if link \( e \) belongs to the primary path \( P_{dp} \) realizing demand \( d \); 0, otherwise.
- \( \mu_{edp} = 1 \) if link \( e \) belongs to the protection path \( R_{dp} \) protecting path \( P_{dp} \) of demand \( d \); 0, otherwise.
- \( \gamma_{geq} = 1 \) if link \( g \) belongs to path \( q \) realizing capacity of link \( e \); 0, otherwise.
- \( \vartheta_{fgz} = 1 \) if link \( f \) belongs to primary path \( Z_g \) realizing capacity of link \( g \); 0, otherwise.
- \( \theta_{fgz} = 1 \) if link \( f \) belongs to the protection path \( A_g \) protecting path \( Z_g \) of link \( g \); 0, otherwise.
- \( \pi_{fgv} = 1 \) if link \( f \) belongs to the path \( v \) realizing capacity of link \( g \); 0, otherwise.
- \( \Delta_{lgr} = 1 \) if link \( l \) belongs to path \( r \) restoring OTN interface \( k \) on link \( g \); 0, otherwise.
- \( M \): Module size for IP/MPLS layer.
- \( U_k \): Module size for OTN layer link capacities \( k = 0, 1, 2, 3, 4 \).
- \( N \): Module size for DWDM layer link capacities.
- \( \eta_e \): Cost of one capacity unit of module \( M \) of IP/MPLS layer link \( e \).
- \( \beta_{gk} \): Cost of one capacity unit of type \( U_k \) of OTN layer link \( g \).
- \( \xi_f \): Cost of one capacity unit of module \( N \) of WDM layer link \( f \).
Notations (Variables)

- $x_{dp}$: IP/MPLS flow allocated to path pair $p$ ($\mathbb{P}_{dp}$, $\mathbb{R}_{dp}$) of demand $d$ (non-negative, binary).
- $m_{eq}$: OTN flow allocated to path $q$ realizing normal capacity of link $e$ (non-negative integral).
- $m'_{eq}$: OTN flow allocated to path $q$ realizing protection capacity of link $e$ (non-negative integral).
- $s_{gkz}$: DWDM flow allocated to path pair $z$ ($\mathbb{Z}_g$, $\mathbb{K}_g$) realizing normal capacity of link $g$ of interface $k$ (non-negative integral).
- $s'_{gkv}$: DWDM flow allocated to path $v$ realizing protection capacity of link $g$ of interface $k$ (non-negative integral).
- $\bar{z}_{gkv}$: DWDM flow allocated to path $v$ realizing OTN capacity of link $g$ of interface $k$ that realizes protection capacity of the IP/MPLS layer (non-negative integral).
- $c_{gkr}$: flow restoring normal capacity of interface $k$ of link $g$ on restoration path $r$.
- $u_{gkr}$: binary flow variable associated with $c_{gkr}$.
- $y_e$: Number of modules $M$ to be installed on link $e$ for normal capacity of the IP/MPLS layer (non-negative integral).
- $y_e'$: Protection capacity on link $e$.
- $w_{gk}$: Number of modules $U_k$ to be installed on link $g$ in the OTN layer (non-negative integral).
- $w_g$: Protection capacity of link $g$ (non-negative integral).
- $w'_{gk}$: Number of modules $U_k$ to be installed on link $g$ in the OTN layer for realizing IP/MPLS layer protection capacity (non-negative integral).
- $b_f$: Number of modules $N$ to be installed on link $f$ in the DWDM layer (non-negative integral).
- $b'_f$: Protection capacity on link $f$ in the DWDM layer (non-negative integral).
- $b''_f$: Number of modules $N$ to be installed on link $f$ in the DWDM layer for realizing OTN layer protection capacity (non-negative integral).
- $b''''_f$: Number of modules $N$ to be installed on link $f$ in the DWDM layer for realizing OTN capacity that realizes IP/MPLS layer protection capacity (non-negative integral).
Constraints

\[
\sum_{p=1}^{D} x_{dp} = 1 \quad d = 1, 2, ..., D \tag{1}
\]

\[
\sum_{d=1}^{D} h_d \sum_{p=1}^{P_d} \delta_{edp} x_{dp} \leq M y_e \quad e = 1, 2, ..., E \tag{2}
\]

\[
\sum_{d=1}^{D} h_d \sum_{p=1}^{P_d} \mu_{edp} x_{dp} \leq M y_e \quad e = 1, 2, ..., E \tag{3}
\]

\[
\sum_{q=1}^{Q_e} m_{eq} = y_e \quad e = 1, 2, ..., E \tag{4}
\]

\[
\sum_{q=1}^{Q_e} m'_{eq} = \underline{y}_e \quad e = 1, 2, ..., E \tag{5}
\]

\[
M \sum_{e=1}^{E} \sum_{q=1}^{Q_e} \gamma_{geq} m_{eq} \leq \sum_{k=0}^{4} U_k w_{gk} \quad g = 1, 2, ..., G \tag{6}
\]

\[
M \sum_{e=1}^{E} \sum_{q=1}^{Q_e} \gamma_{geq} m'_{eq} \leq \sum_{k=0}^{4} U_k w'_{gk} \quad g = 1, 2, ..., G \tag{7}
\]

\[
\sum_{r=1}^{R_g} c_{gkr} = w_{gk} \quad g = 1, 2, ..., G \quad k = 0, 1, 2, 3, 4 \tag{8}
\]

\[
\sum_{r=1}^{R_g} u_{gkr} = 1 \quad g = 1, 2, ..., G \quad k = 0, 1, 2, 3, 4 \tag{9}
\]
Optimal Solution: Minimum numbers of capacity modules (IP/MPLS layer), OTN signals (OTN layer), and wavelengths (DWDM layer), for each capacity component.
Cost Model

Upper layer interface

Lower layer interface

Multiplexing cost

OTN signal interface

OXC port

Transponder

Interface Physical to physical

Physical distance

\[ \eta_e = 2 \eta_e^U + 2 \eta_e^L \]

\[ \beta_{gk} = \beta_{g}^U + \beta_{g}^k \]

\[ \xi_f = 2(\xi_f^I + \xi_f^t + \xi_f^o) + \Delta_f \]
Large number of constraints:
- \( D + 4(E + GR + F + G^2) + 22G \)

Large number of variables:
- \( P \cdot D + 2(E(1+Q)) + 8G(1+R) + 12GZ + 4F \)

Integer Linear Programming model.

Simpler forms of network design problems are NP-hard.

The problem is difficult to solve using an ILP solver even for small size networks.
Three-Phase Solution Approach

**Phase 1:** Solve the following design problem:

Minimize \( \sum_{e=1}^{E} \eta_e (y_e + y'_e) + \sum_{g=1}^{G} \sum_{k=0}^{4} \beta_{gk} (w_{gk} + w'_{gk}) \) \hspace{1cm} (20)

subject to the set of constraints (1)–(7). Then, \( w_{gk} \) will be a constant in the phase 2.

**Phase 2:** Solve the following design problem:

Minimize \( \sum_{g=1}^{G} \sum_{k=0}^{4} \beta_{gk} w_{gk} + \sum_{f=1}^{F} \xi_f b'_f \) \hspace{1cm} (21)

subject to the set of constraints (8)–(11), (13), and (17).

**Phase 3:** Solve the following design problem:

Minimize \( \sum_{f=1}^{F} \xi_f (b_f + b'_f + b''_f) \) \hspace{1cm} (22)

subject to the set of constraints (12), (14)–(16), and (18).
Parameters Values:
cost ratio of network elements:
Transponder, IP/optical interface, OXC → 8, 0.5, 1
Transform values: $M=10$, $\text{IP-cost}=5 \rightarrow \text{U}_0\text{-cost}=2$, $\text{W-cost}=140$
Avoid unrealistic $U_k$-cost relationships:

$U_k = U_{k+1}$

E.g. $1U_1 = 1U_2$ (equal cost of two different signals)

or $4U_k = U_{k+1}$

E.g. $4U_2 = U_3$ (follows a multiplexing rule)

or $4U_k > U_{k+1}$

E.g. $4U_2 > U_3$ ($U_2$ usage significantly shrinks)

Avoid similar-performance $U_k$-cost relationships:

$1.5 \ U_k = U_{k+1}$

E.g. $1.5 \ U_2 = U_3$ (close behavior to $2U_k = U_{k+1}$)

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### UK-cr1:

$2 \ U_k = U_{k+1}$

$2/4/8/16/32$

### UK-cr2:

$3 \ U_k > U_{k+1}$

$2/5/13/20/50$

### UK-cr3:

$3 \ U_k = U_{k+1}$

$2/6/18/54/162$
14-node NSFNET.
- 42 nodes and 63 links.
- 91 demands. Avg. = 5 Gbps.
- IP=5, M=2.5, UK-cr1.
Notation – Abbreviation Mapping

<table>
<thead>
<tr>
<th>Notation</th>
<th>Abbreviation</th>
<th>Discretion</th>
</tr>
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<tbody>
<tr>
<td>$y_e$</td>
<td>N-IP</td>
<td>Normal IP capacity</td>
</tr>
<tr>
<td>$y_i$</td>
<td>P-IP</td>
<td>Protection IP capacity</td>
</tr>
<tr>
<td>$w_{gk}$</td>
<td>N-OTN</td>
<td>Normal OTN capacity</td>
</tr>
<tr>
<td>$w'_{gk}$</td>
<td>P-OTN</td>
<td>Protection OTN capacity</td>
</tr>
<tr>
<td>$w''_{gk}$</td>
<td>P-IP-OTN</td>
<td>OTN capacity of P-IP</td>
</tr>
<tr>
<td>$b_f$</td>
<td>N-W</td>
<td>Normal fiber capacity</td>
</tr>
<tr>
<td>$b_f'$</td>
<td>P-W</td>
<td>Protection fiber capacity</td>
</tr>
<tr>
<td>$b''_f$</td>
<td>P-OTN-W</td>
<td>Fiber capacity of P-OTN</td>
</tr>
<tr>
<td>$b'''_f$</td>
<td>P-IP-OTN-W</td>
<td>Fiber capacity of P-IP-OTN</td>
</tr>
</tbody>
</table>
Basic Questions:
- How do the IP-cost and the size of $M$ influence the required protection capacity at each layer and the overall network cost?
- How does the cost of each $U_k$ scenario affect the final types and numbers of $U_k$s needed to satisfy a given set of demands?

Reported results:
- Total Cost.
- Capacity of different component.
- Protection Capacity.
- OTN Signals.
- Cost vs. Capacity.
• The larger the $M$ the more demands it can satisfy without increasing the cost.
• When $M$ and the IP-cost are fixed, the case of UK-cr3 is the most expensive followed by UK-cr2 and UK-cr1. This is because the gap between the Uk-cost is the largest in UK-cr3.
• The cost gap between UK-cr3 and UK-cr2 is larger than between UK-cr2 and UK-cr1.
• Protection capacity of each layer is larger than its normal capacity.
• The gap between the normal capacity and its protection capacity increases as we go down in the network’s layers.
• This is primarily due to the larger granularity of the lower layers and the longer the protection paths.
• The gap is the largest in the DWDM layer where each wavelength bit rate N=100 Gbps.
• We note the same trends for different IP-cost and UK-cost scenarios.
**P-IP:** *M=10 requires more protection capacity. *M=2.5 is the best case to minimize P-IP. *IP-cost is not a significant factor when M=2.5 unlike the case when M=10.

**P-OTN:** *The smallest required protection capacity achieved under UK-cr3 and the largest under UK-cr2. *The case when M=2.5 is often the case that minimizes P-OTN.

**P-W:** *UK-cr3 ➔ best case to minimize this capacity component*
In UK-cr3, only U0 and U3 are used.
In UK-cr2, U4 is used but with fewer numbers than U3.
In UK-cr1, U4 becomes higher than U3 due to the small gap between their costs.
Low numbers of U1s and U2s in all cases.
The cost gap between UK-cr3 and UK-cr2 is larger than between UK-cr2 and UK-cr1. This is because of the costs of the Uks used in each Uk-cost scenario.

Ex: To consume the full capacity of an OTN link (100 Gbps):
- In UK-cr1, optimal solution would be to use 1 U4, cost=32.
- In UK-cr2, optimal solution would also be 1 U4, costs=50.
- In UK-cr3, U4 is not the optimal solution since 2U3 + 16U0 = 140 < 162, the cost of a U4.
- The gap between UK-cr1 and UK-cr2 in this example is (50 − 32 = 18, or about a 56% increase).
- On the other hand, the gap between UK-cr2 and UK-cr3 is (140 − 50 = 90, or about a 180% increase).
Previously we observed that $M=10 \rightarrow$ lowest overall network cost performance when the IP-cost is fixed.

This may seem contradictory to the observation that $M=10 \rightarrow$ more capacity is often required.

However, note the cost per Gbps and modularity effects:
- Ex. when IP-cost=40, the costs per Gbps are 16 and 4 for the cases $M=2.5$ and $10$.
- To carry 11 Gbps:
  - Cost: $5 \times M=200$ ($M=2.5$) > $2 \times M=80$ ($M=10$).
  - **Cost perspective**: Higher $M \rightarrow$ lower cost.
  - Capacity: $5 \times M=12.5$ Gbps ($M=2.5$) < $2 \times M=20$ Gbps ($M=10$).
  - **Capacity perspective**: Higher $M \rightarrow$ higher capacity.
The case when M is above the average demand would be the best case to reduce the overall network cost, it is often the one that requires more protection capacity.

The case when M is below the average demand would achieve the lowest amount of capacity needed for protection at each layer.

The protection capacity of each layer is larger than its normal capacity, noticeably at the lowest layer (DWDM layer), due to the longer protection paths and the larger granularity of this layer.

The limited usage of OTN layer U1 and U2 signals. Mainly, the IP/MPLS demands will be accommodated by U0s and U3s under UK-cr3 or a mix of U4 and U3 with very low numbers of U0s, U1s, or U2s, under UK-cr1 and UK-cr2.

For future work, we plan to:

- Expand our study by developing a heuristic algorithm to solve the problem for large size networks.
- Provide an extensive analysis.
- Consider other protection mechanisms and compare their performance under the three-layer architecture.