MULE: Multi-Layer Virtual Network Embedding

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Virtual Network Embedding (VNE)
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Extensive Literature, mostly focused on single-layer substrate
Multi-Layer IP-over-Optical Network

IP Network
- Packet Switched
- Flexible addressing, traffic engineering, resource allocation
Multi-Layer IP-over-Optical Network

Optical Network

- Circuit switched
- High capacity (Terabits of bandwidth/link)
Multi-Layer IP-over-Optical Network

IP overlay on Optical Network

- IP routers are directly connected to optical switches
- IP links are logical and tunneled over optical paths
- Best of two worlds
- High capacity combined with flexible addressing, routing, traffic engineering, resource allocation.
Multi-Layer IP-over-DWDM Network
Multi-Layer IP-over-DWDM Network

IP Links are tunneled over a single wavelength light-path
Multi-Layer IP-over-OTN Network

OTN Links are logical, routed over wavelengths, and can multiplex bandwidth of multiple IP Links.
Topological Flexibility of Multi-Layer Network
Topological Flexibility of Multi-Layer Network

New IP Links can be created on-the-fly
Question:

How can we leverage the topological flexibility of multi-layer networks for VN embedding?
(One Possible) Answer:
If IP network does not have sufficient capacity for VN embedding, then we can increase capacity, by creating new IP links
The Problem

**Multi-Layer Virtual Network Embedding (MULE)**

In the most resource efficient way, jointly determine
The Problem

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- Embedding of new IP Links on Optical Layer
Context

Multi-Layer IP-over-OTN Network

OTN is static and OTN Links are already provisioned on light-paths in DWDM layer.

No multi-path embedding; No node capacities
MULE: Example

Given

Multi-Layer Substrate Network
MULE: Example

Given

Multi-Layer Substrate Network

Logical IP Layer

Physical Optical Layer
MULE: Example

Given

Logical IP Layer

Physical Optical Layer

Multi-Layer Substrate Network

Virtual Network (VN)

Location Constraint
MULE: Example

Embed the VN on the IP Layer
MULE: Example

Embed the VN on the IP Layer

Create new IP links (if necessary)
MULE: Example

Embed the VN on the IP Layer

Create new IP links (if necessary)

Embed the new IP links on Optical Layer
MULE: Example

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Objective: Minimize bandwidth allocation cost on both layers
Our Contributions

A suit of solutions to MULE

**OPT-MULE**
ILP-based Optimal Solution (NP-hard)

**FAST-MULE**
Three Step Heuristic: Collapse, Extract, Embed
## State-of-the-art

### D-VNE*
- No Optimal Solution
- Collapses multiple layers into one with information loss
- Two step virtual node and virtual link embedding

### MULE
- ILP-based Optimal Solution
- Collapses multiple layers into one without information loss
- Jointly embeds virtual nodes and links as much as possible

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OPT-MULE: ILP model for optimal solution to MULE that minimizes bandwidth allocation cost for embedding VN and provisioning new IP links.
**OPT-MULE**

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FAST-MULE: Challenges
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Challenge - I

Joint Embedding on IP and Optical Layer
**FAST-MULE: Challenges**

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FAST-MULE: Challenges

**Challenge - I**
Joint Embedding on IP and Optical Layer

**Solution**
Collapse IP and Optical Layer into a single layer

**Challenge - II**
Joint embedding of virtual nodes and virtual links

**Solution**
Embed star subgraphs from VN in a single shot using min-cost max-flow
FAST-MULE: 3-Phase Algorithm
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Phase-I (Collapse): Collapse IP and Optical Layers into a single layer collapsed graph
FAST-MULE: 3-Phase Algorithm

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Phase-II (Extract): Extract star subgraphs from VN
FAST-MULE: 3-Phase Algorithm

Phase-I (Collapse): Collapse IP and Optical Layers into a single layer collapsed graph

Phase-II (Extract): Extract star subgraphs from VN

Phase-III (Embed): Jointly embed nodes and links of each star subgraph on the collapsed graph
Phase-I: Collapse
Phase-I: Collapse

Place as many direct links as the number of ports of an IP node to the corresponding OTN node (set bandwidth to port capacity)
Phase-I: Collapse

- Place IP links between OTN nodes where the link’s IP endpoints are.
- Keep IP link cost as is, set OTN link cost to very high.
Phase-II: Extract

Extract star-shaped subgraph from VN

Embedding a star-shaped subgraph in one-shot corresponds to jointly embedding a virtual node and all its incident virtual links.
Phase – III: Embed

We reduce star-subgraph embedding to solving min-cost max-flow on collapsed graph.
Phase – III: Embed

Map center node of star to one of its location constraint IP node.
Phase-III: Embed

Add meta-node for each other Vnode.
Phase-III: Embed

Add link from a VNode's location constraint nodes to its meta-node.
Phase-III: Embed

Add a sink node (t). Add unit capacity link from all meta-nodes to sink node.
Phase-III: Embed

Set cap. of other links to: max. number of VLinks that can be placed on that link
Phase-III: Embed

Solve min-cost max-flow to obtain joint node and link embedding.
Evaluation: Setup

- FAST-MULE compared with OPT-MULE and D-VNE*
- OTN
  - 15 – 100 nodes
- IP Network
  - ~60% the size of the OTN
- Virtual Network
  - 4 – 8 nodes
  - 20 VNs for each IP/OTN combination

FAST-MULE Performance Highlights

Optimal for star shaped VN*

* Proof is in the paper
FAST-MULE Performance Highlights

- Optimal for star shaped VN*
- 67% better than D-VNE on avg.

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FAST-MULE Performance Highlights

- Optimal for star shaped VN*
- 67% better than D-VNE on avg.
- Within ~47% of optimal on avg.
- 2-3 Orders of magnitude faster than OPT-MULE

* Proof is in the paper
We address VNE problem for Multi-Layer IP-over-OTN Network

Two Solutions to MULE: OPT-MULE, FAST-MULE

FAST-MULE performs ~47% better than the optimal (empirically); allocates ~66% less resources than the state-of-the-art
What's Next?

- Can we exploit topological flexibility for failure recovery?
- What is the impact of fragmentation?
- How challenging is it to address MULE for other Optical network technologies (e.g., Elastic Optical Networks)?
Backup Layer
FAST-MULE: Complexity

\( O(|V'||V||E|^2 \log V) \)

- \( V' = \) Number of Virtual nodes
- \( V = \) Number of nodes in collapsed graph
- \( E = \) Number of links in collapsed graph
Conflict Resolution using “Referee Node”

Add meta link:  
Conflicting node $\rightarrow$ referee node $\rightarrow$ meta-node
Impact of Virtual Node Ordering

Fixed substrate size
Why MULE?
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