MULE: Multi-Layer Virtual Network Embedding

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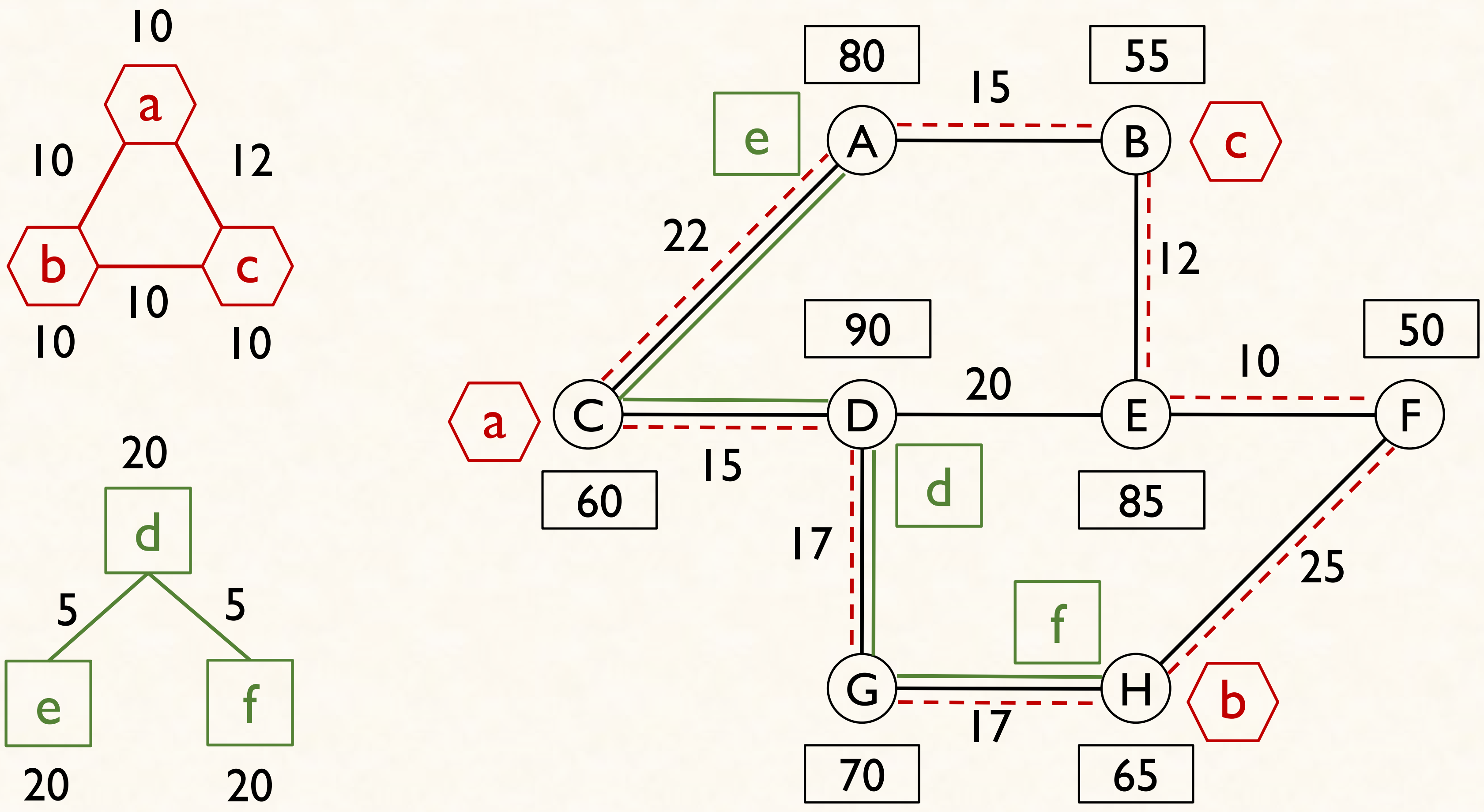
Virtual Network Embedding (VNE)



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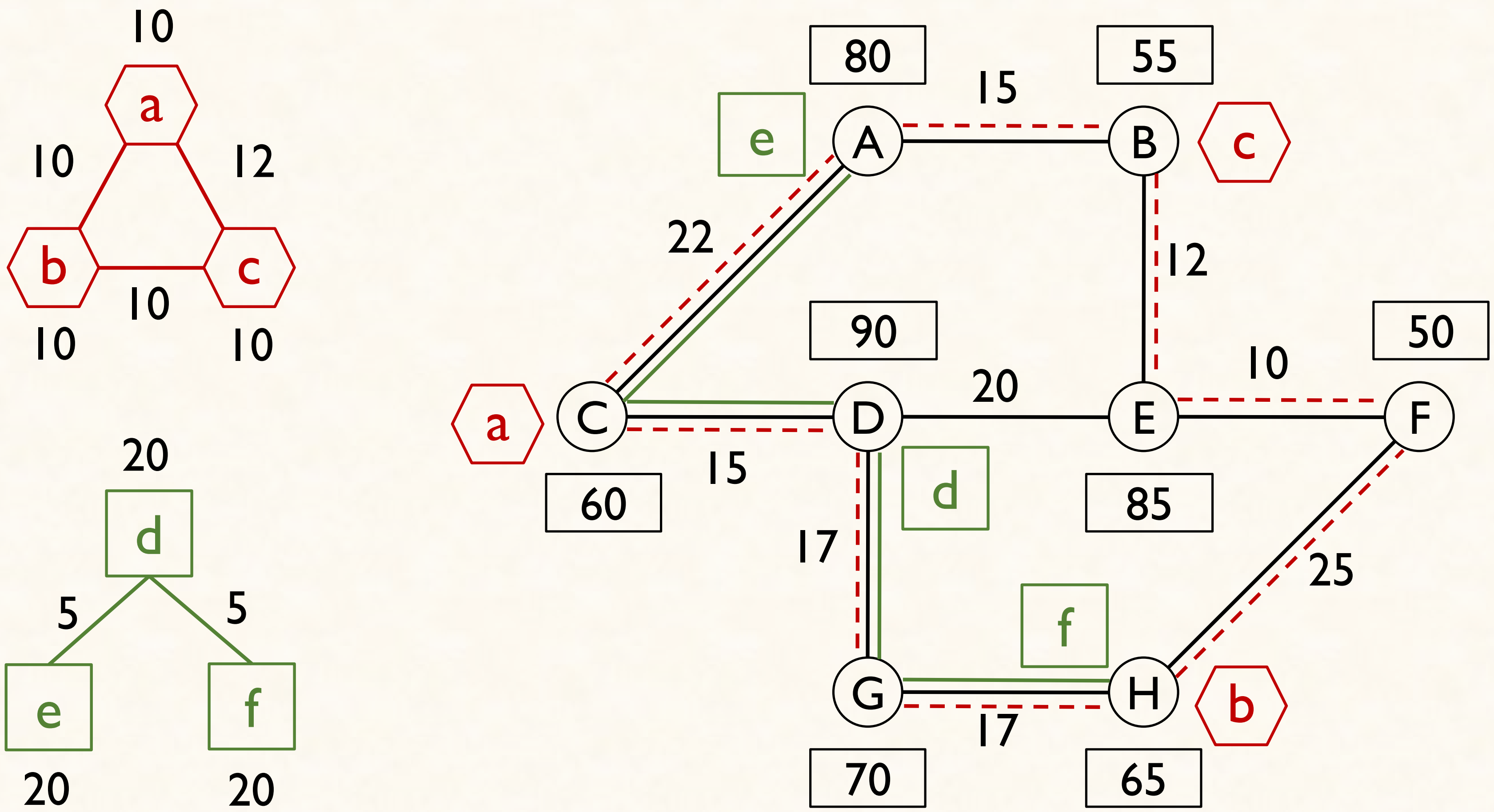
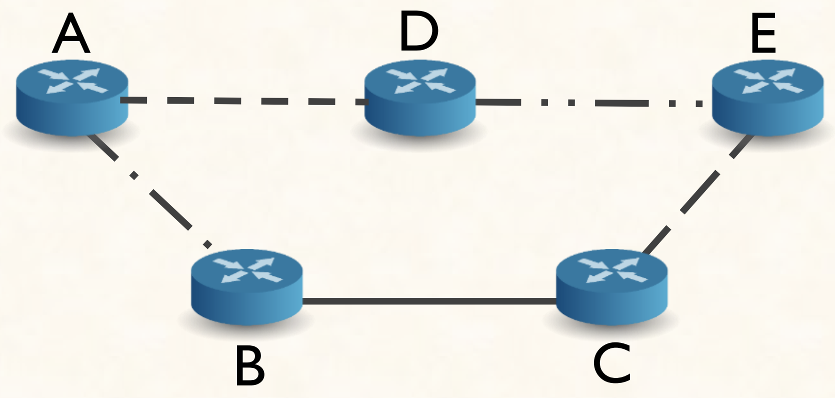


Extensive Literature, mostly focused on single-layer substrate

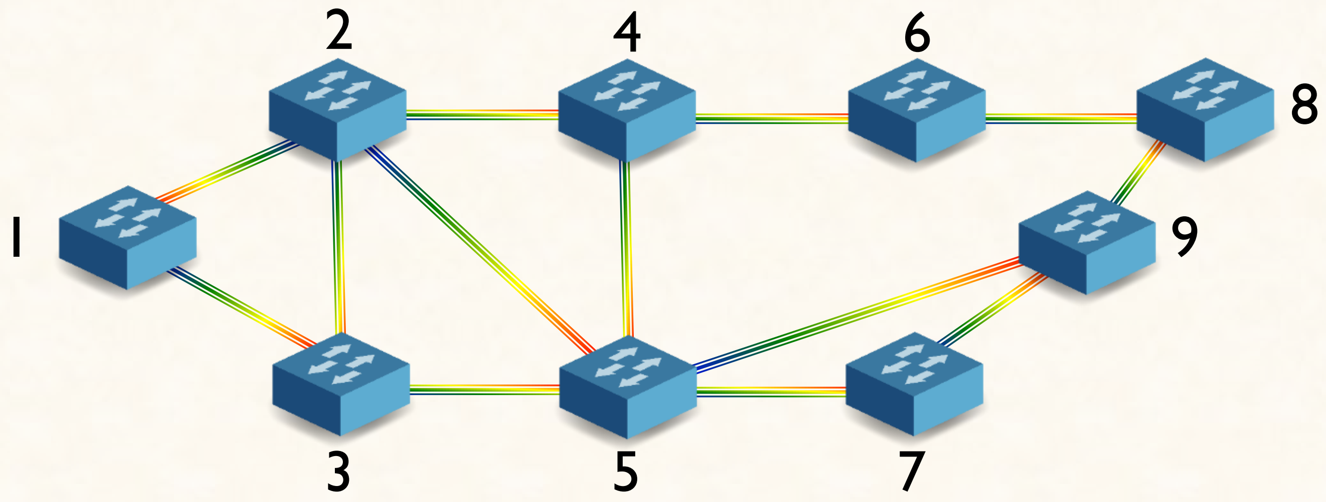
Multi-Layer IP-over-Optical Network



IP Network

- Packet Switched
- Flexible addressing, traffic engineering, resource allocation

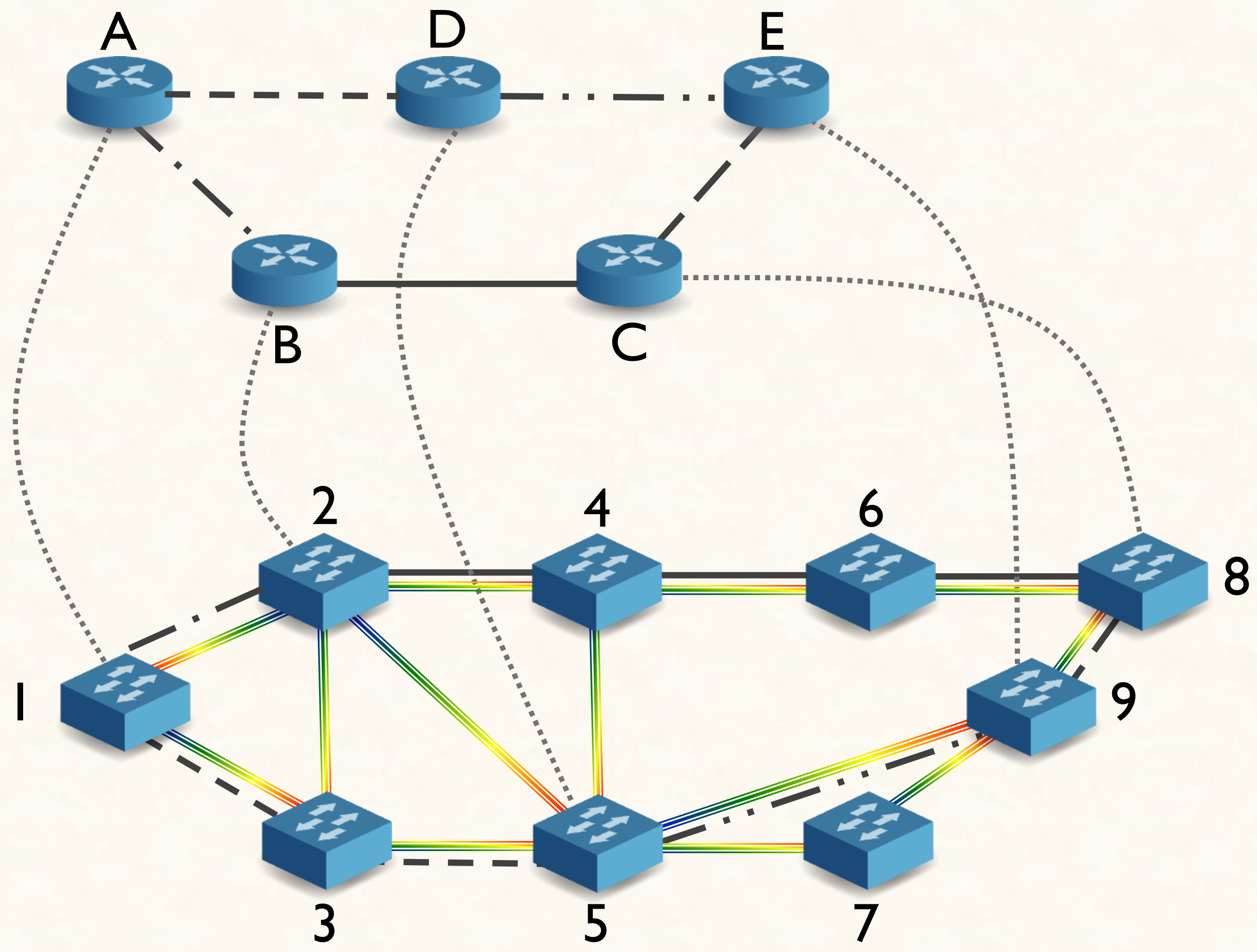
Multi-Layer IP-over-Optical Network



Optical Network

- Circuit switched
- High capacity (Terabits of bandwidth/link)

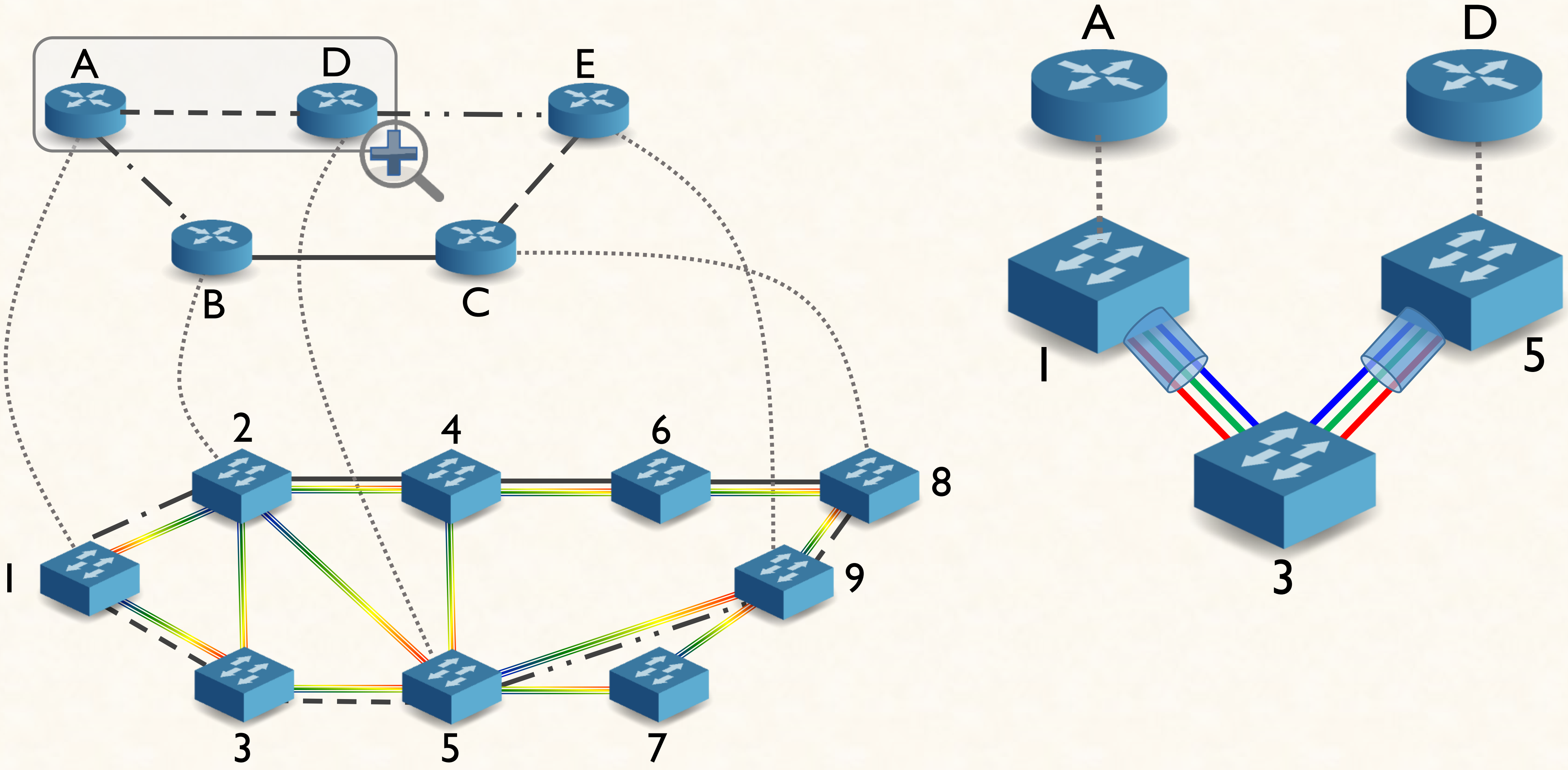
Multi-Layer IP-over-Optical Network



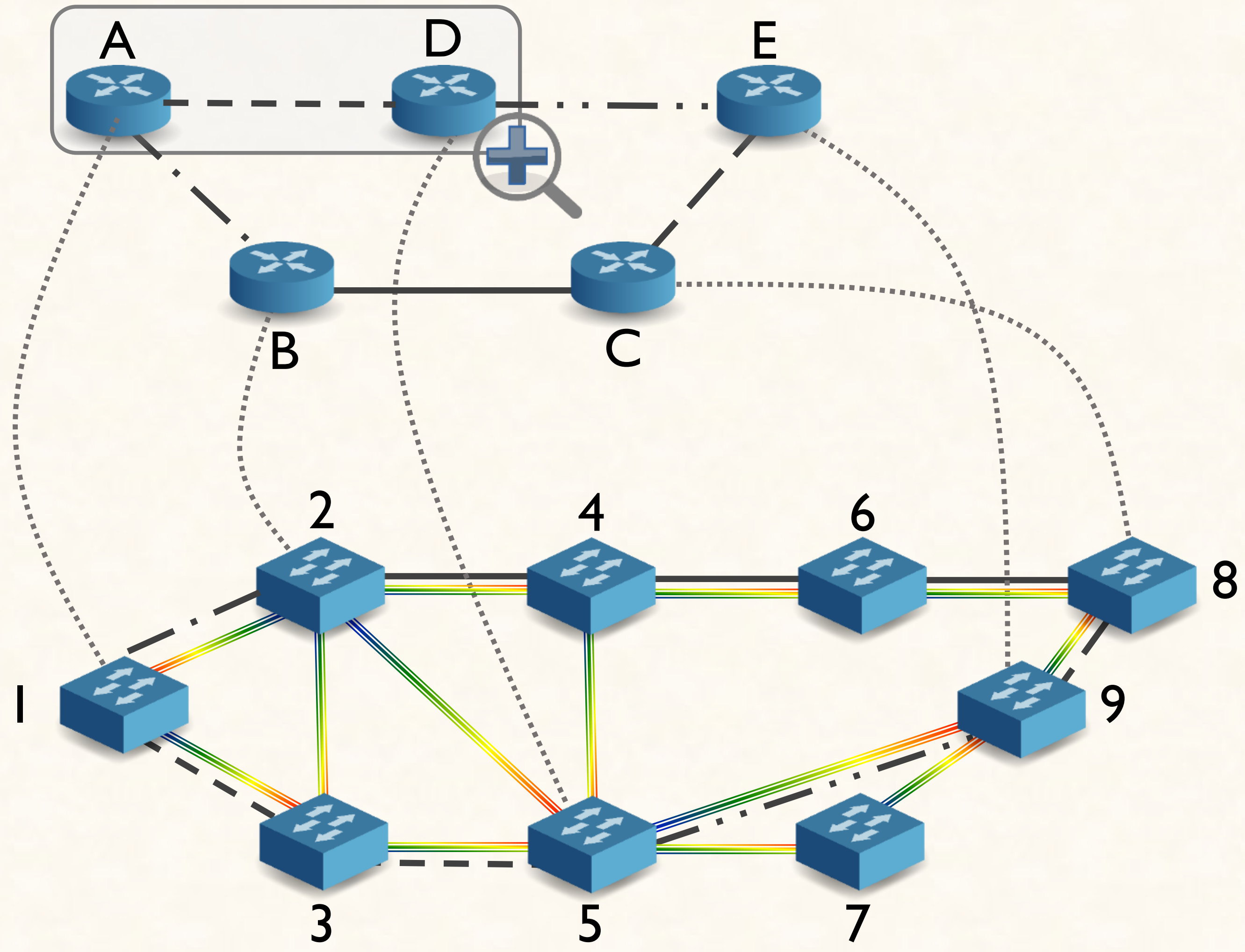
IP overlay on Optical Network

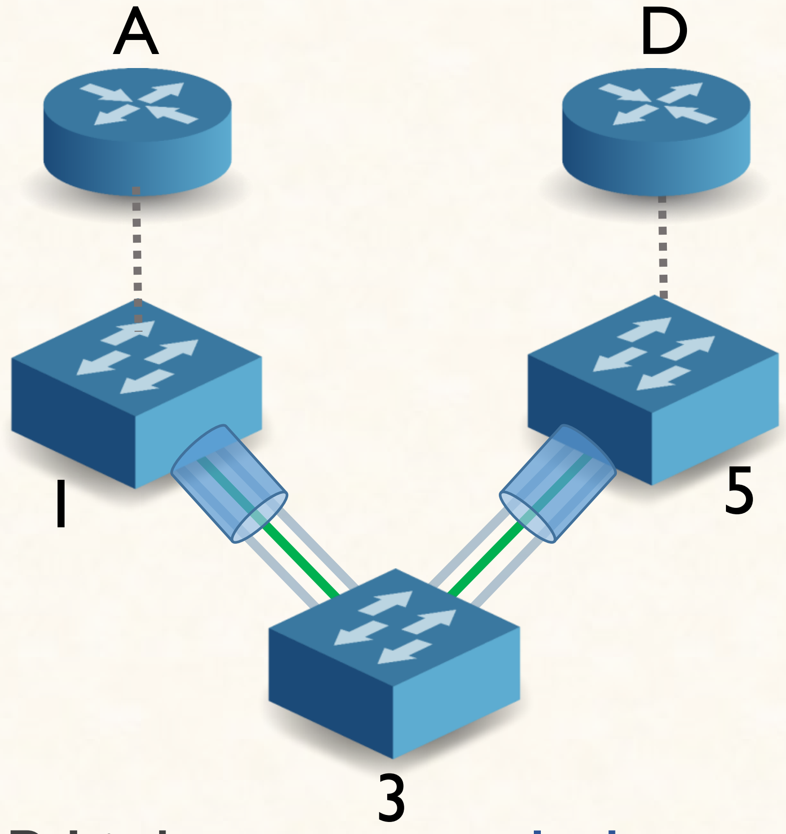
- IP routers are directly connected to optical switches
- IP links are logical and tunneled over optical paths
- Best of two worlds
- High capacity combined with flexible addressing, routing, traffic engineering, resource allocation.

Multi-Layer IP-over-DWDM Network



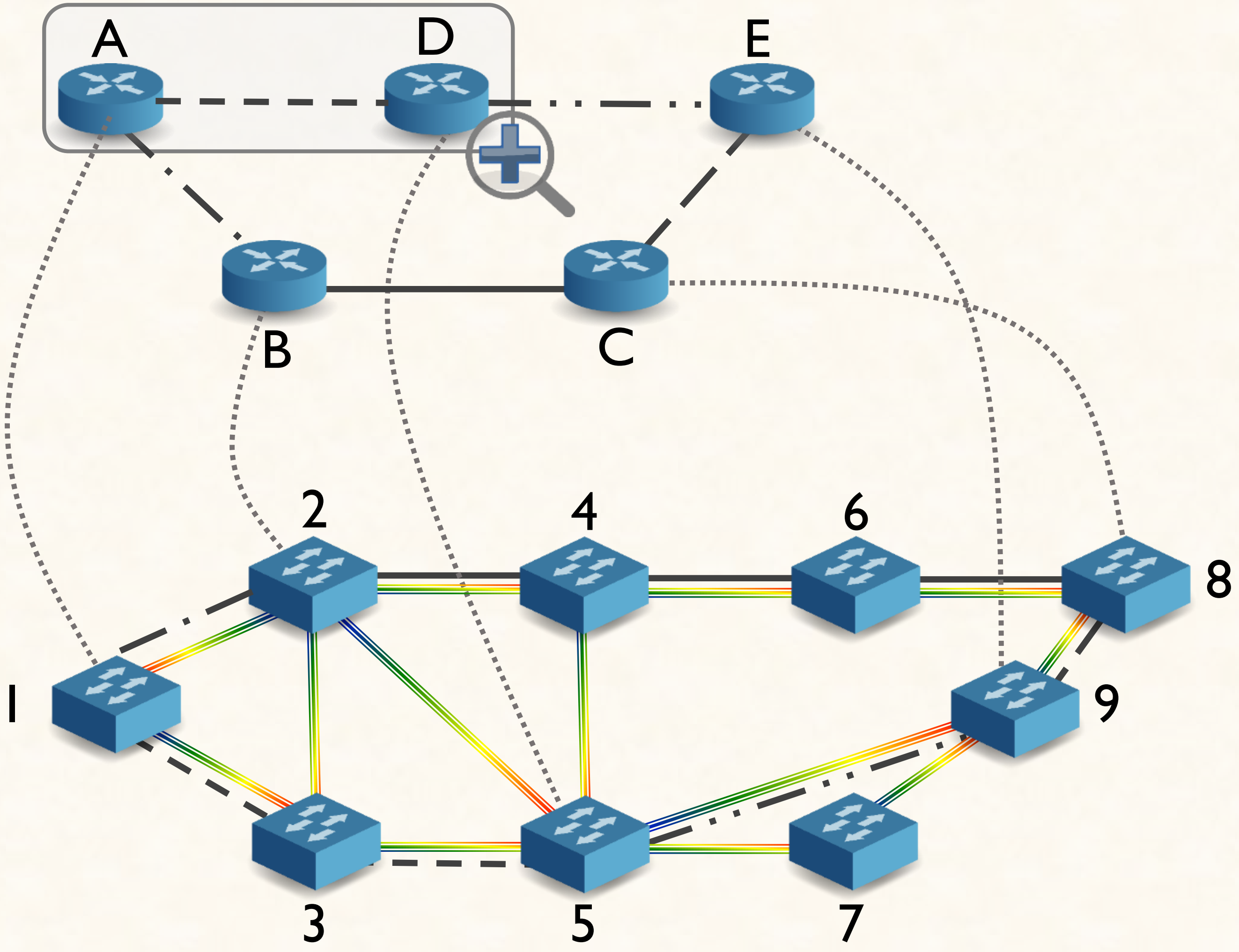
Multi-Layer IP-over-DWDM Network

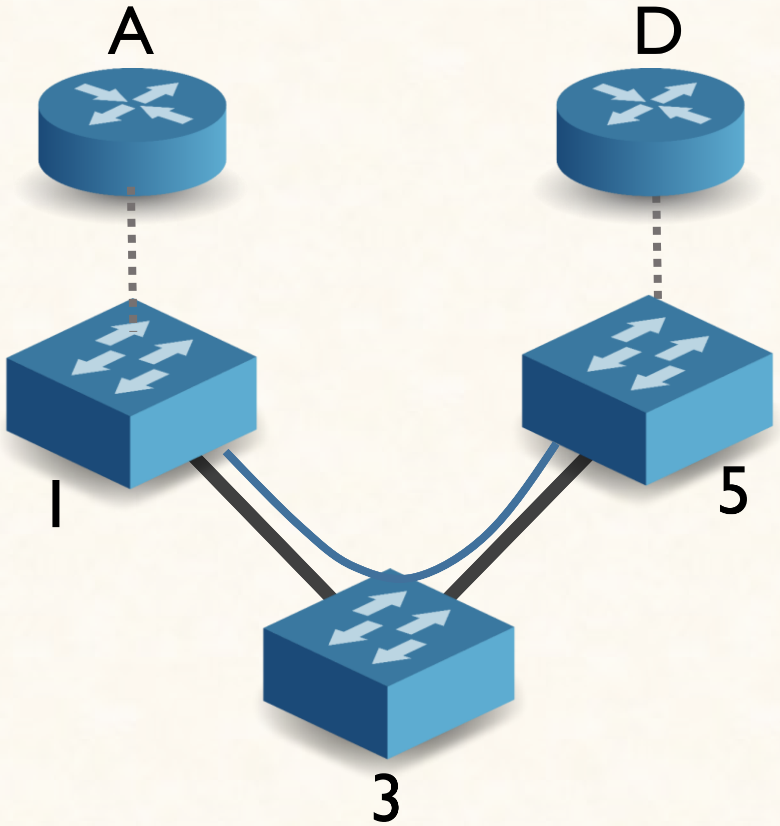




IP Links are tunneled over
a single wavelength light-path

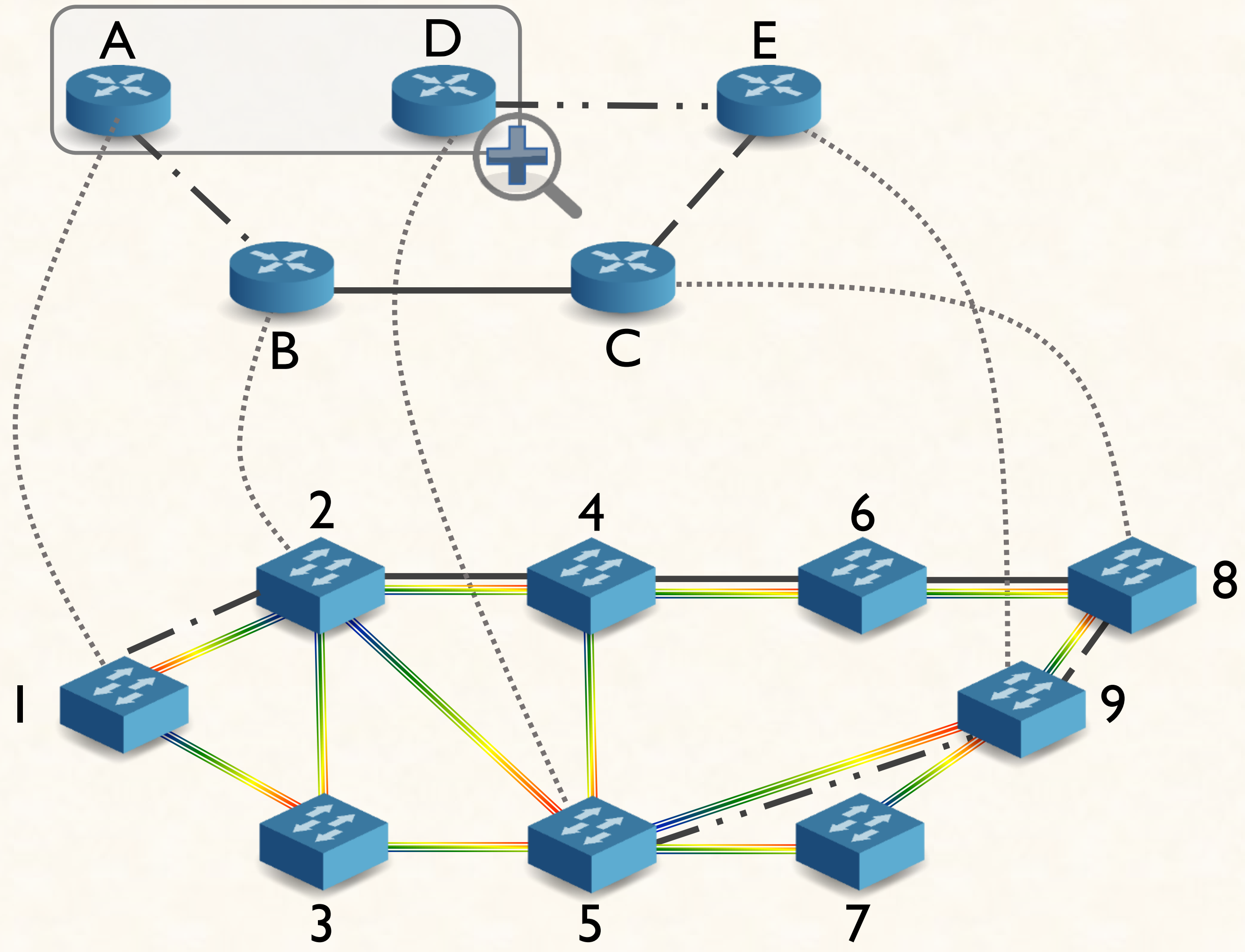
Multi-Layer IP-over-OTN Network

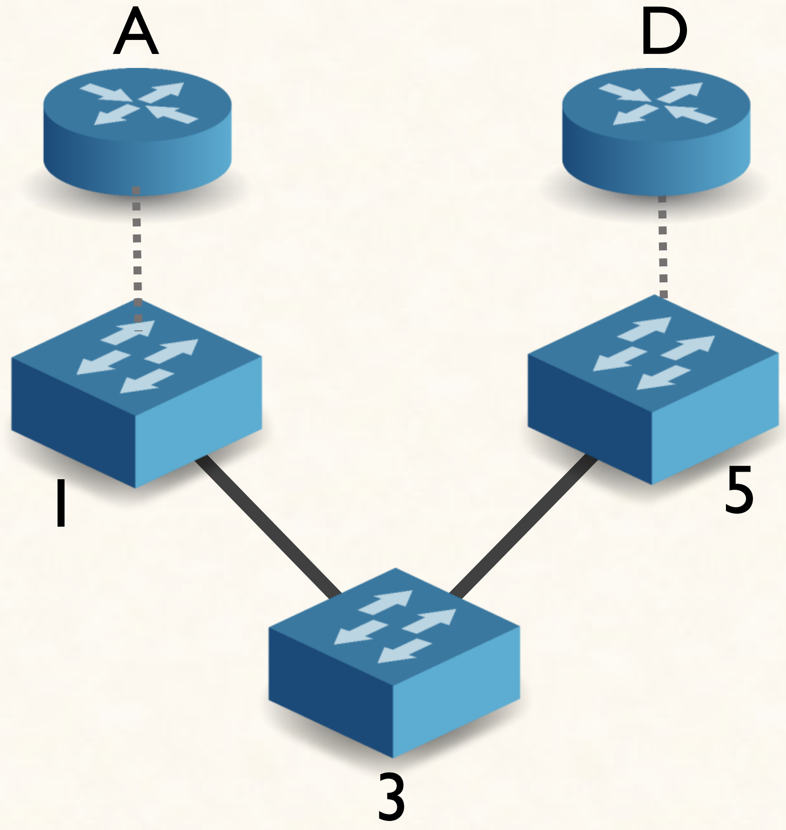




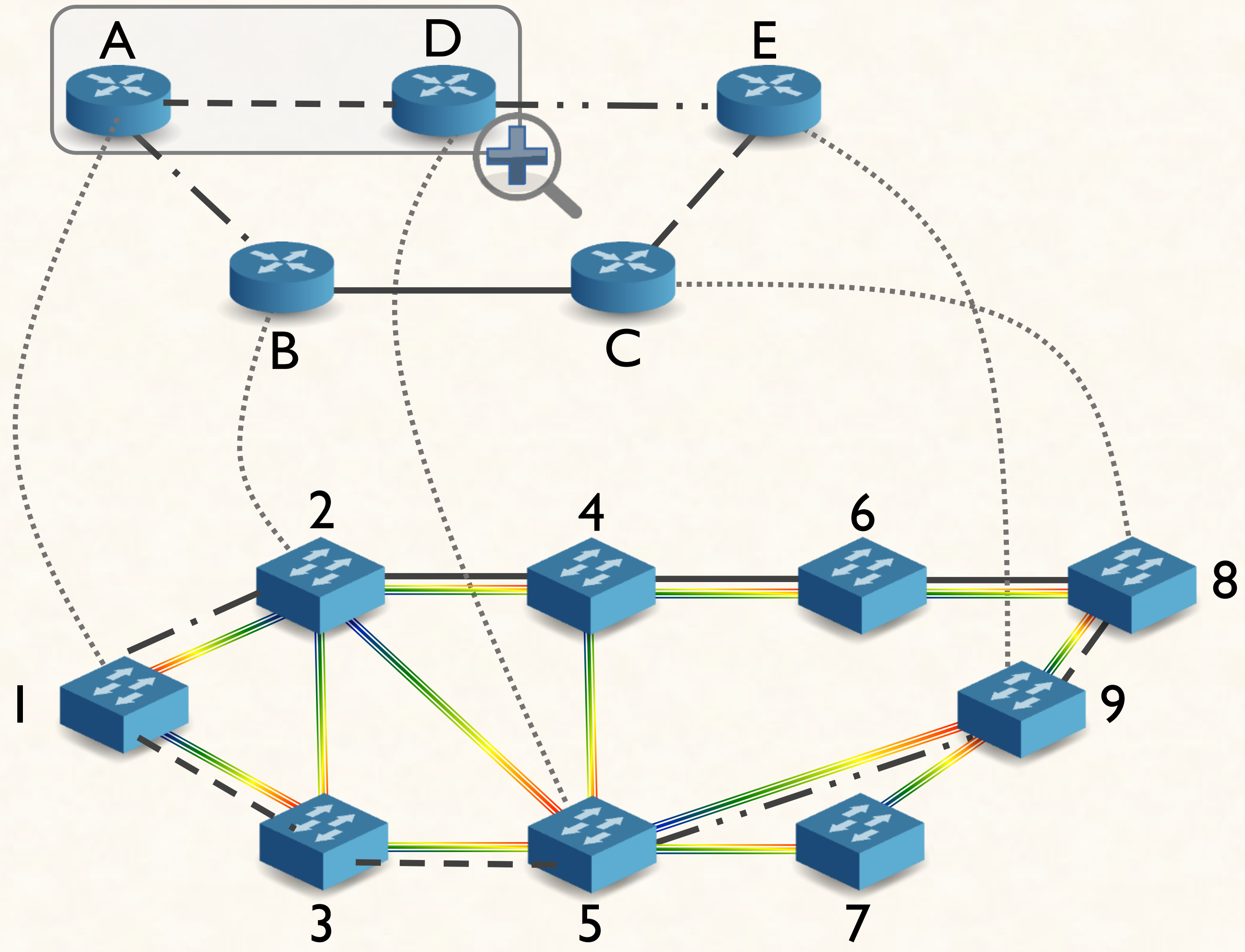
OTN Links are logical, routed over wavelengths, and can multiplex bandwidth of multiple IP Links

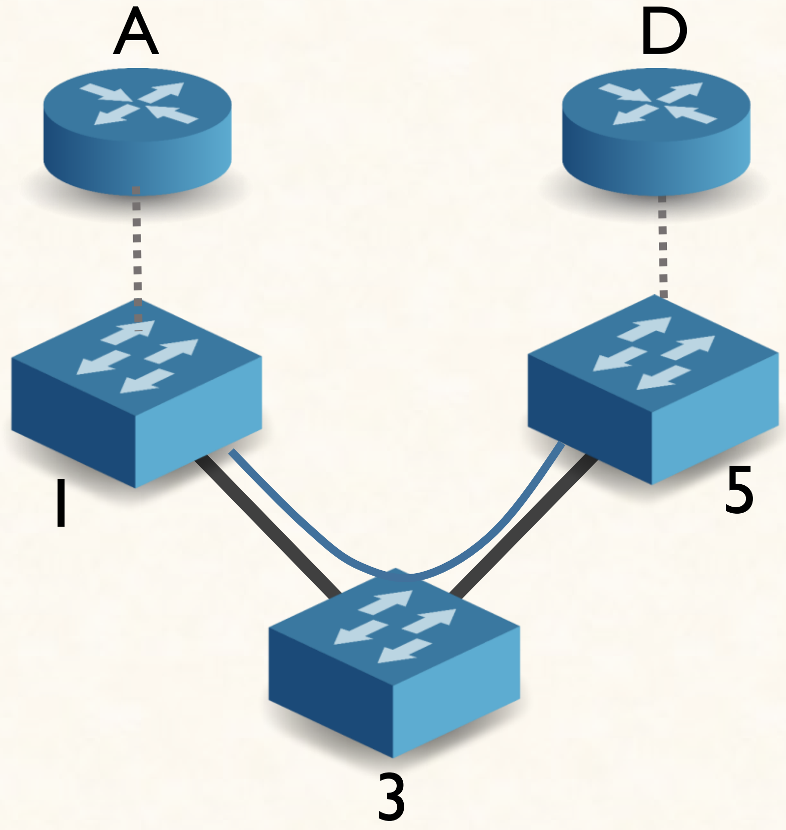
Topological Flexibility of Multi-Layer Network





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

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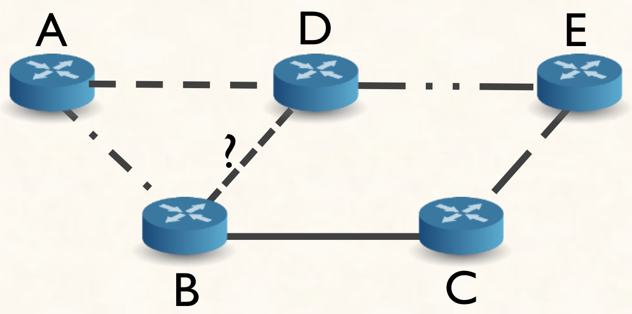
In the most resource efficient way, jointly determine

Creation of New IP links (if necessary)

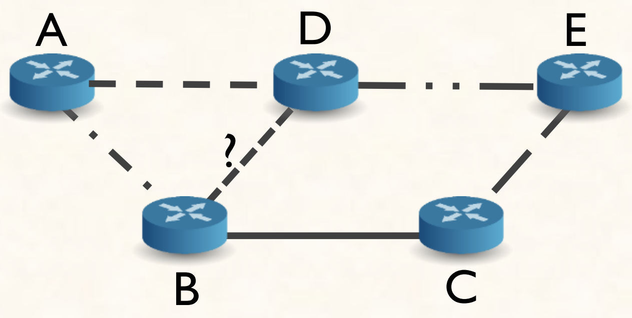


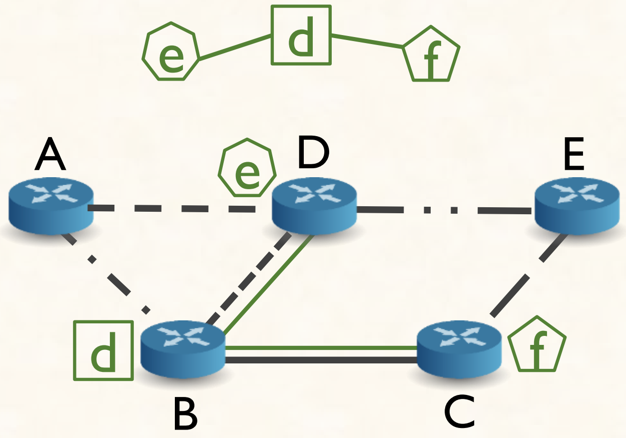
The Problem

Multi-Layer Virtual Network Embedding (*MULE*)

In the most resource efficient way, jointly determine

Creation of New IP links (if necessary)	VN Embedding on the IP Layer



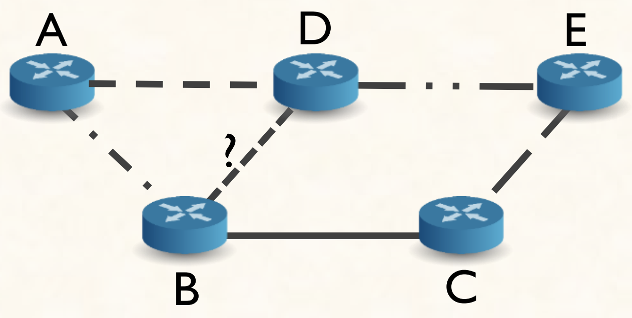


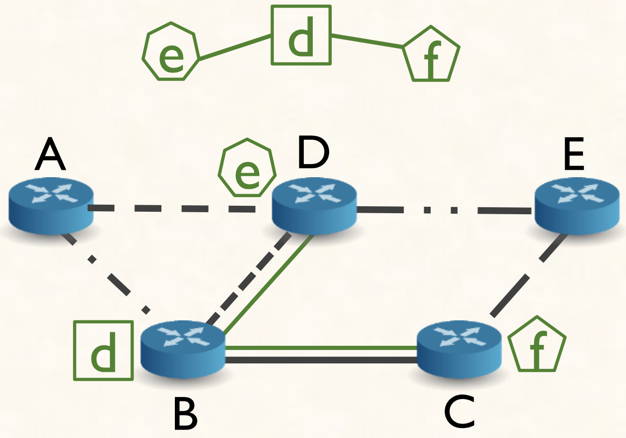
The Problem

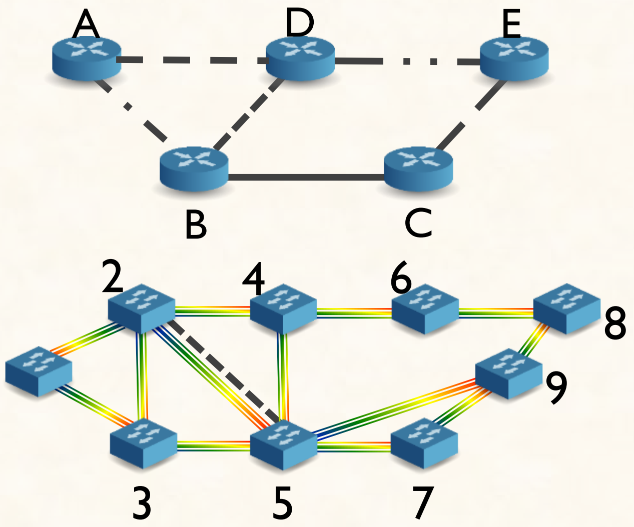
Multi-Layer Virtual Network Embedding (*MULE*)

In the most resource efficient way, jointly determine

Creation of New IP links (if necessary)	VN Embedding on the IP Layer	Embedding of new IP Links on Optical Layer







Context

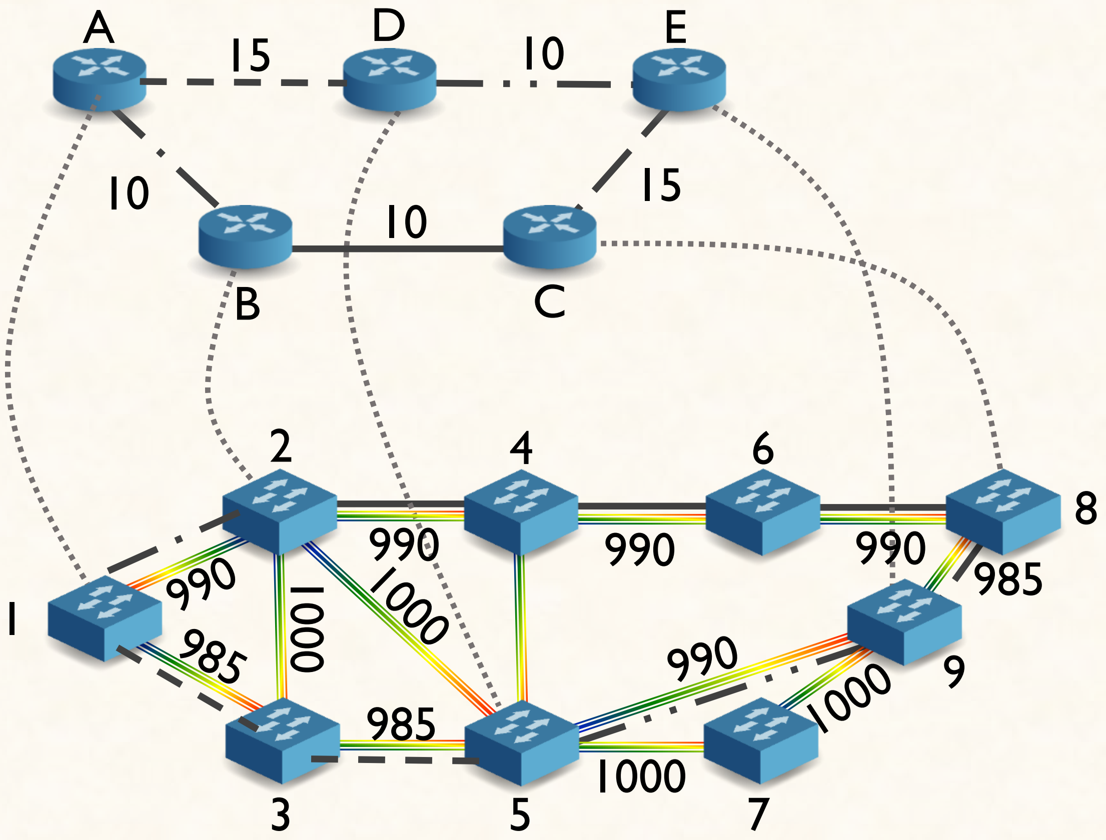
Multi-Layer IP-over-OTN Network

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

No multi-path embedding; No node capacities

MULE: Example

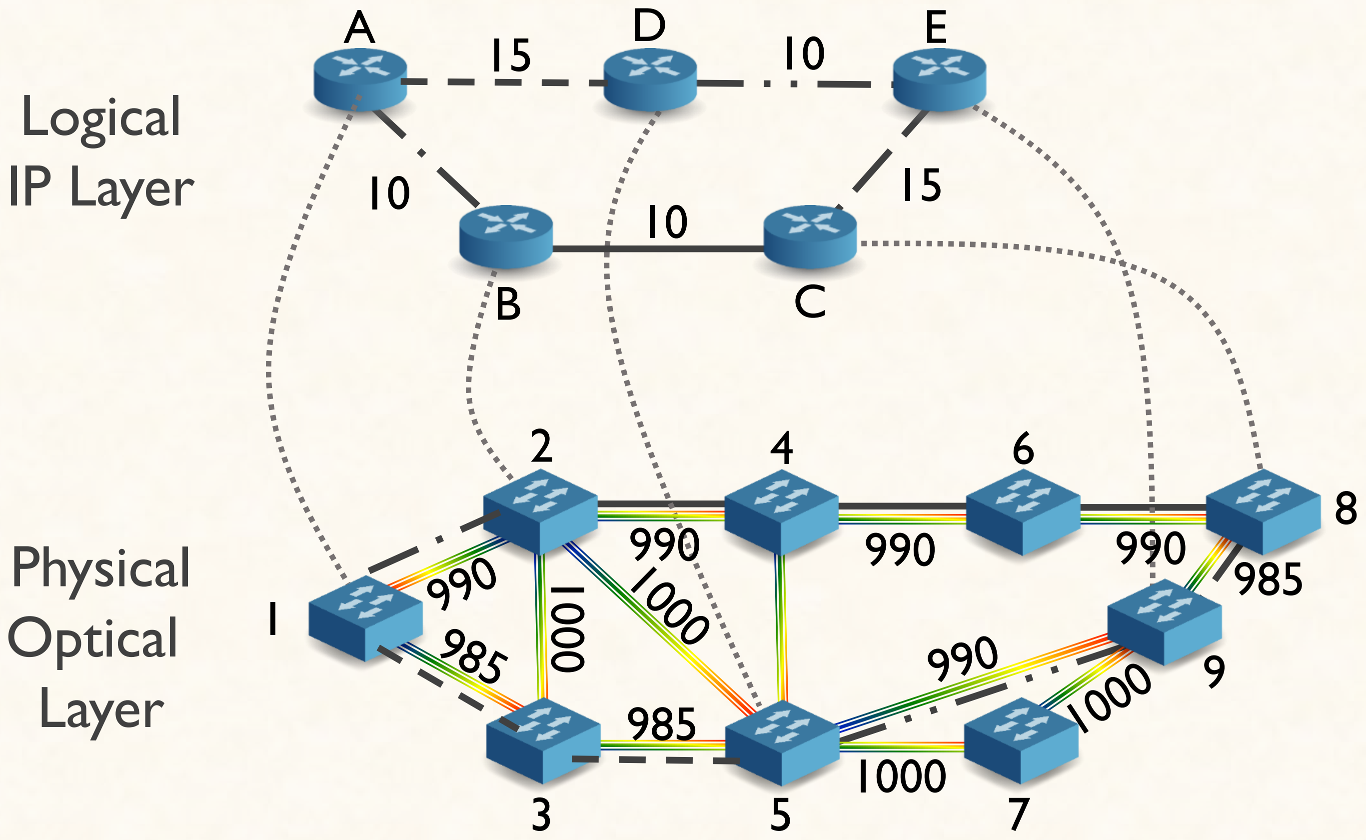
Given



Multi-Layer Substrate Network

MULE: Example

Given



Multi-Layer Substrate Network

MULE: Example

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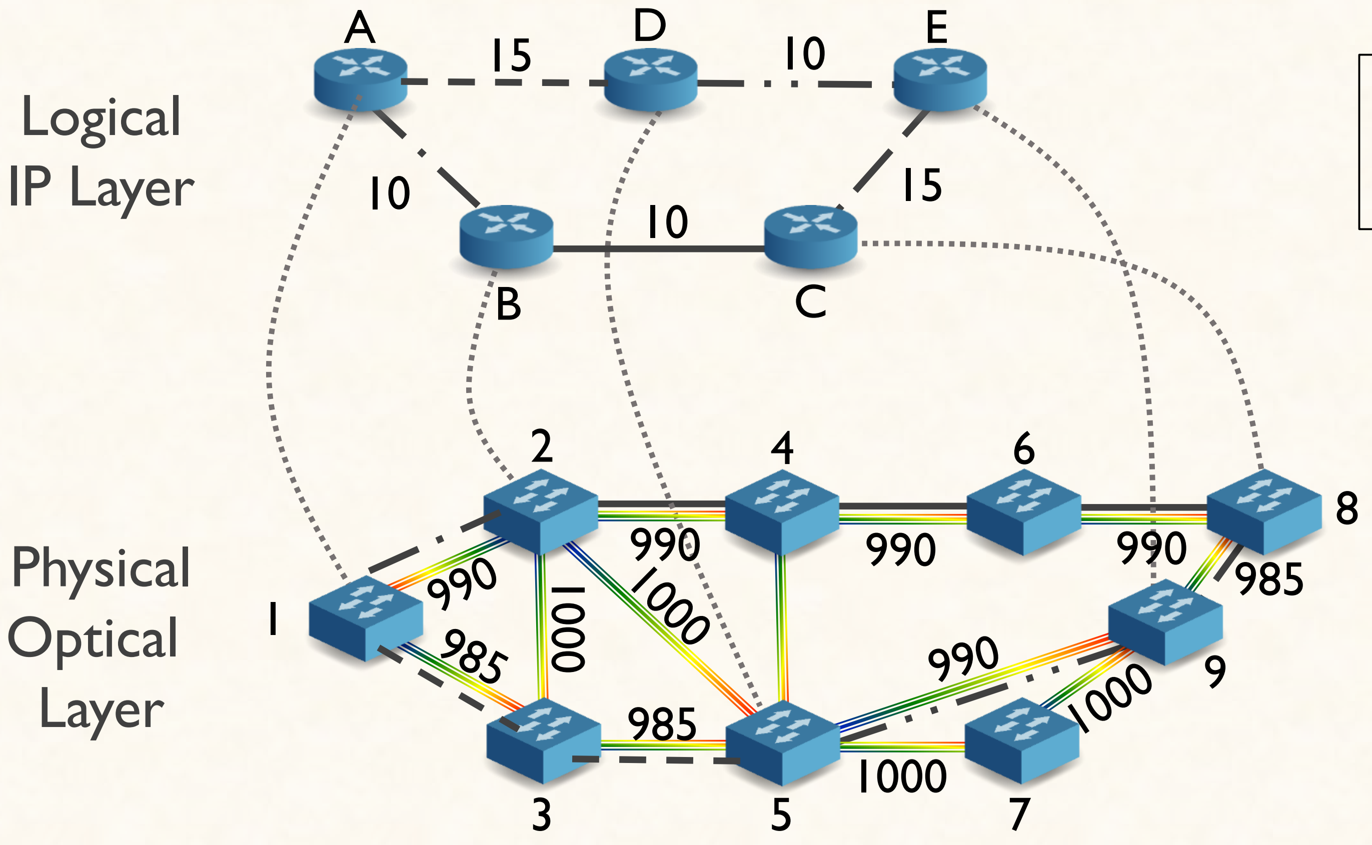
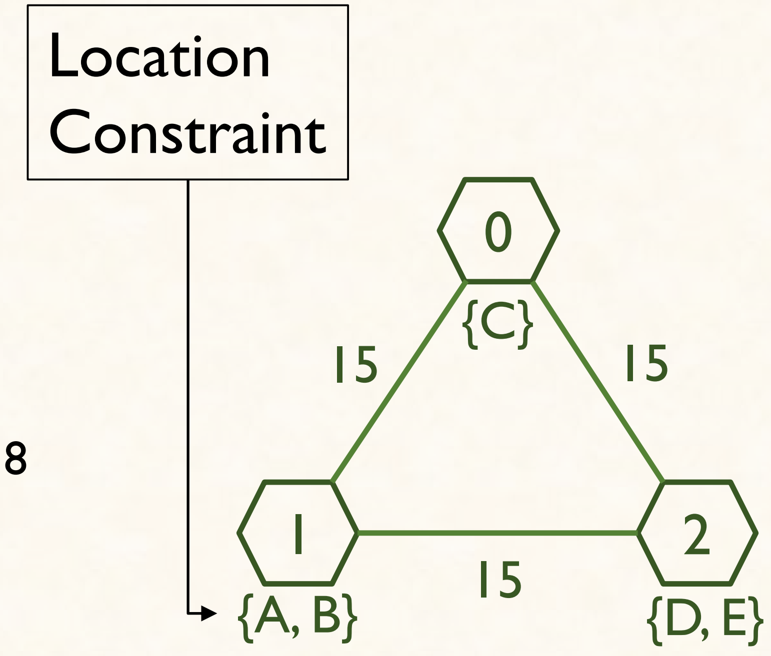


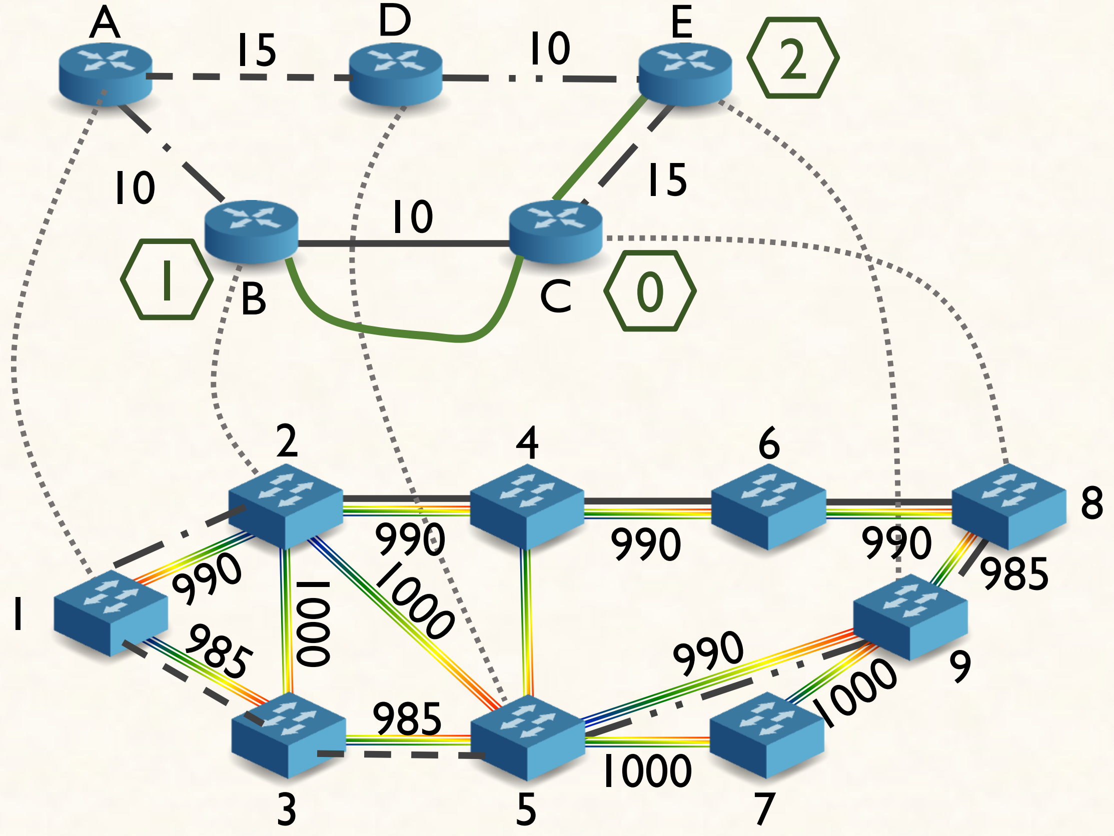
Multi-Layer Substrate Network



Virtual Network (VN)

MULE: Example

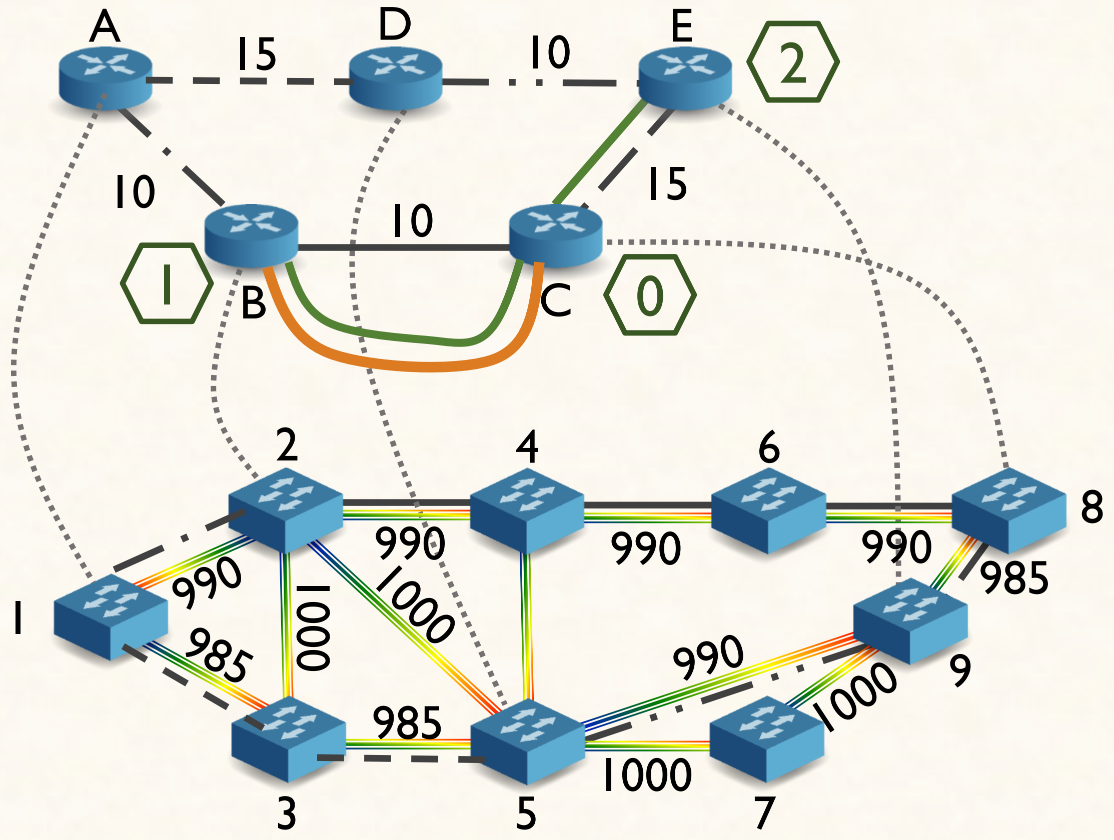
Embed the VN on the IP Layer



MULE: Example

Embed the VN on the IP Layer

Create new IP links (if necessary)

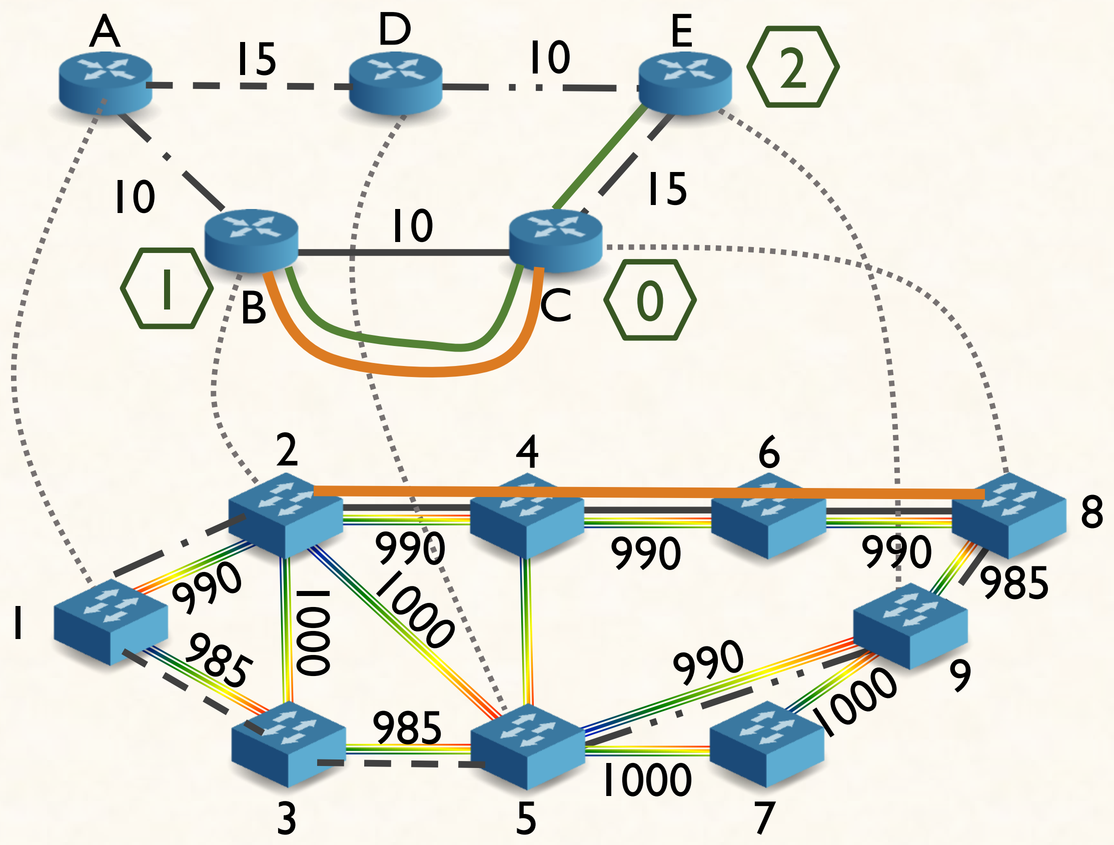


MULE: Example

Embed the VN on the IP Layer

Create new IP links (if necessary)

Embed the new IP links on Optical Layer



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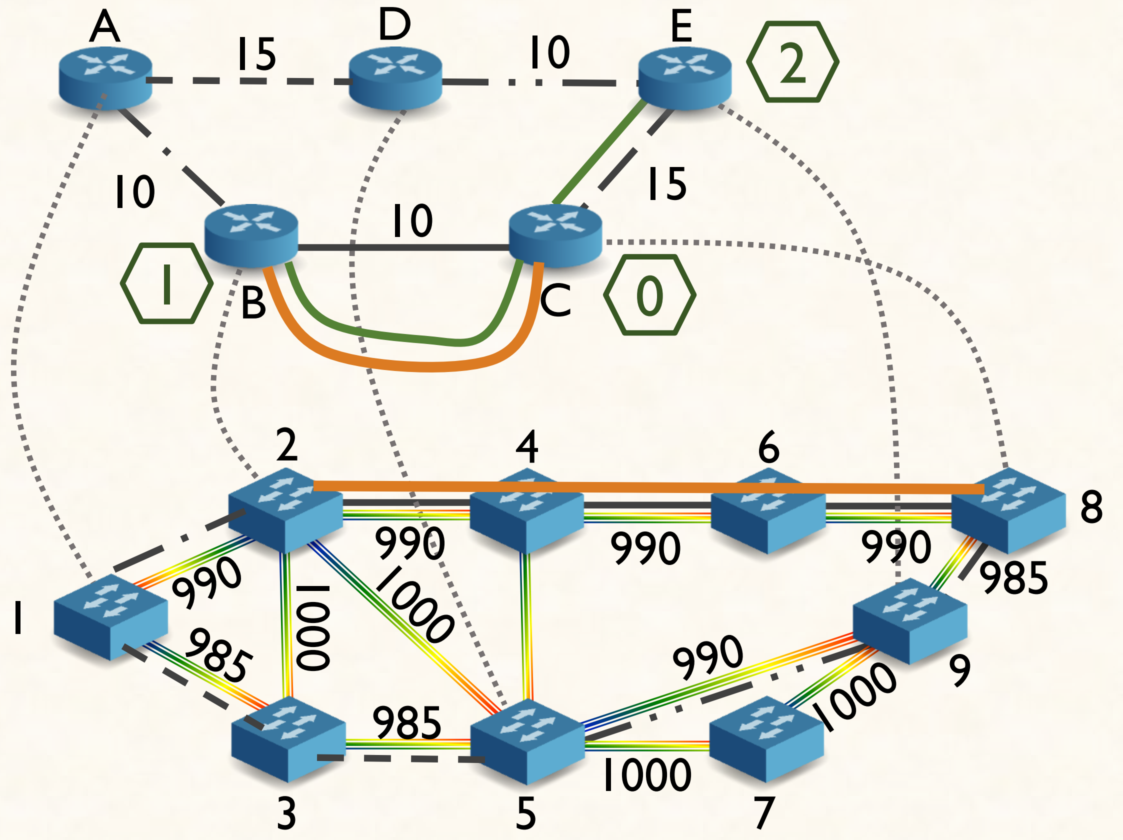

Objective: Minimize bandwidth allocation cost on both layers

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*	MULE
No Optimal Solution	ILP-based Optimal Solution
Collapses multiple layers into one with information loss	Collapses multiple layers into one without information loss
Two step virtual node and virtual link embedding	Jointly embeds virtual nodes and links as much as possible

* Zhang, *et al.* "Dynamic virtual network embedding over multilayer optical networks“, *Journal of Optical Communications and Networking* 7(9): 918-927, 2015.

OPT-MULE:

ILP model for optimal solution to MULE that minimizes bandwidth allocation cost for embedding VN and provisioning new IP links

OPT-MULE*

Decision Variables

Creation of new IP Links, IP Layer to Optical Layer Embedding for new IP links, Virtual Node and Link mapping

Constraints

- Typical VN Embedding constraints for VN to IP Layer Mapping
- Newly created IP links must be embedded on the Optical layer
- Port constraint for IP nodes
- Capacity constraint for OTN links,

* Details are in the paper

OPT-MULE*

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- Virtual links can be mapped to existing or newly created IP links
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FAST-MULE: Challenges

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Challenge - I

Joint Embedding on IP and Optical Layer

FAST-MULE: Challenges

Challenge - I

Joint Embedding on IP and Optical Layer

Solution

Collapse IP and Optical Layer into a single layer

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

FAST-MULE: Challenges

Challenge - I	Solution
Joint Embedding on IP and Optical Layer	Collapse IP and Optical Layer into a single layer

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

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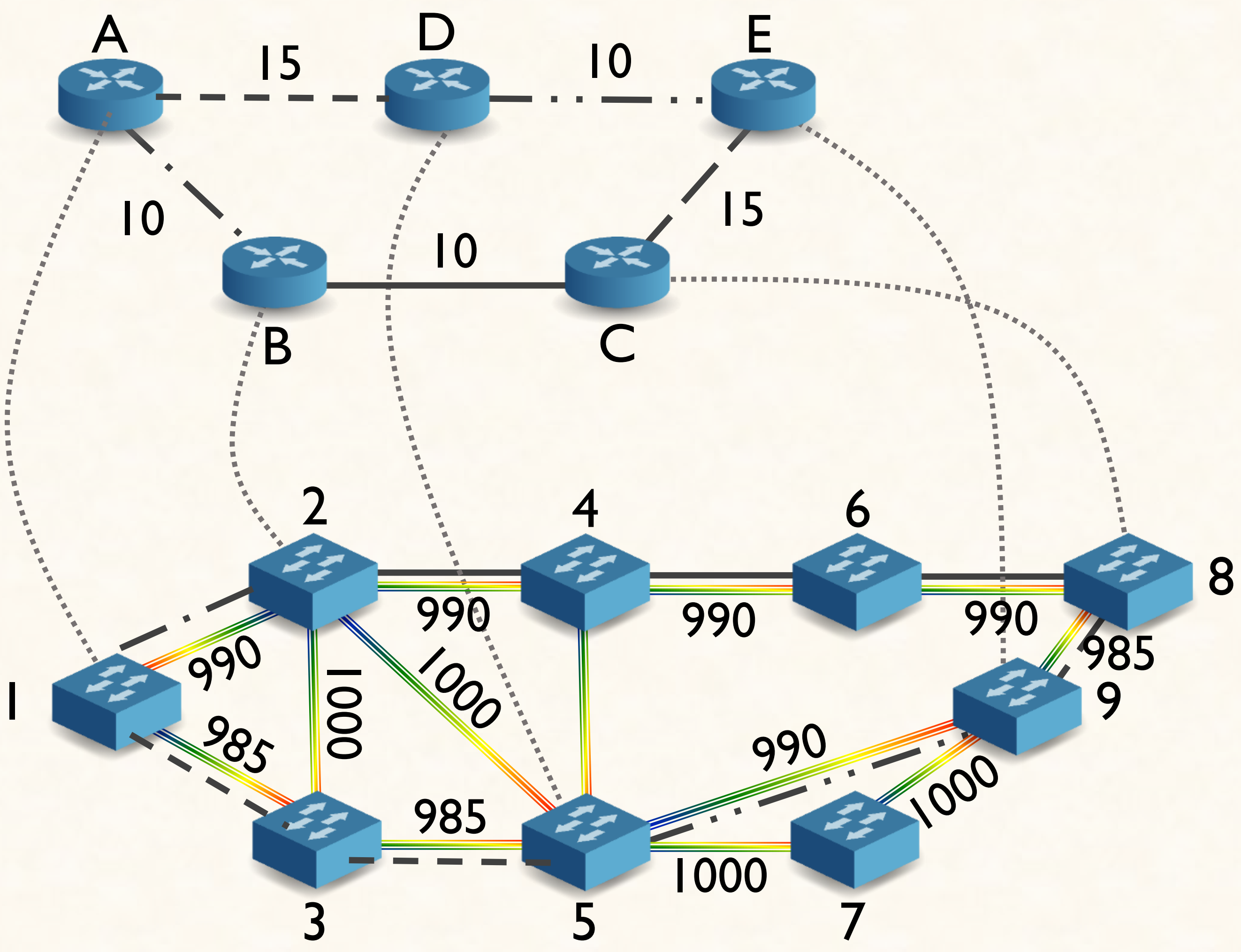
FAST-MULE: 3-Phase Algorithm

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

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

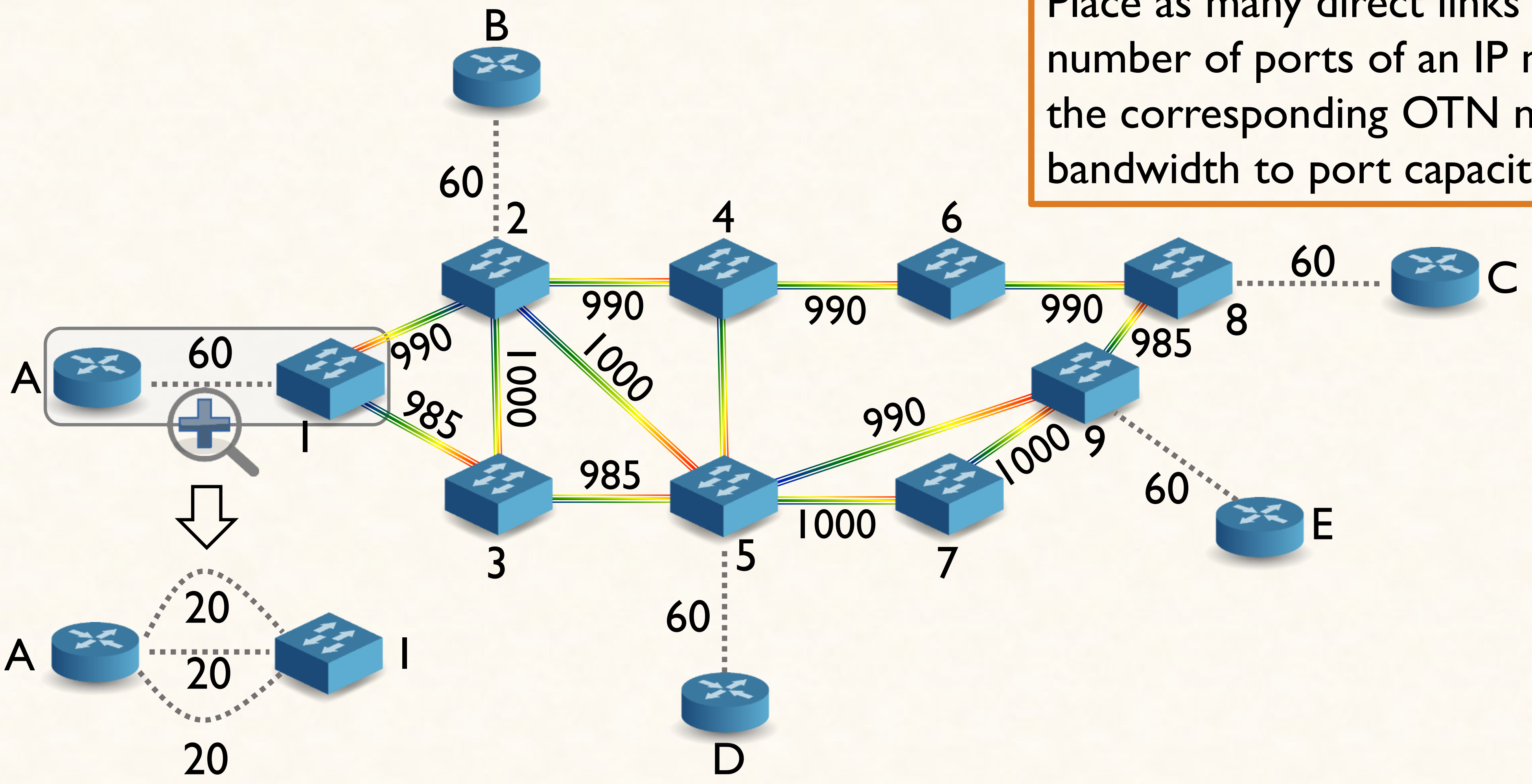
Phase-III (Embed): Jointly embed nodes and links of each star subgraph on the collapsed graph

Phase-I: Collapse

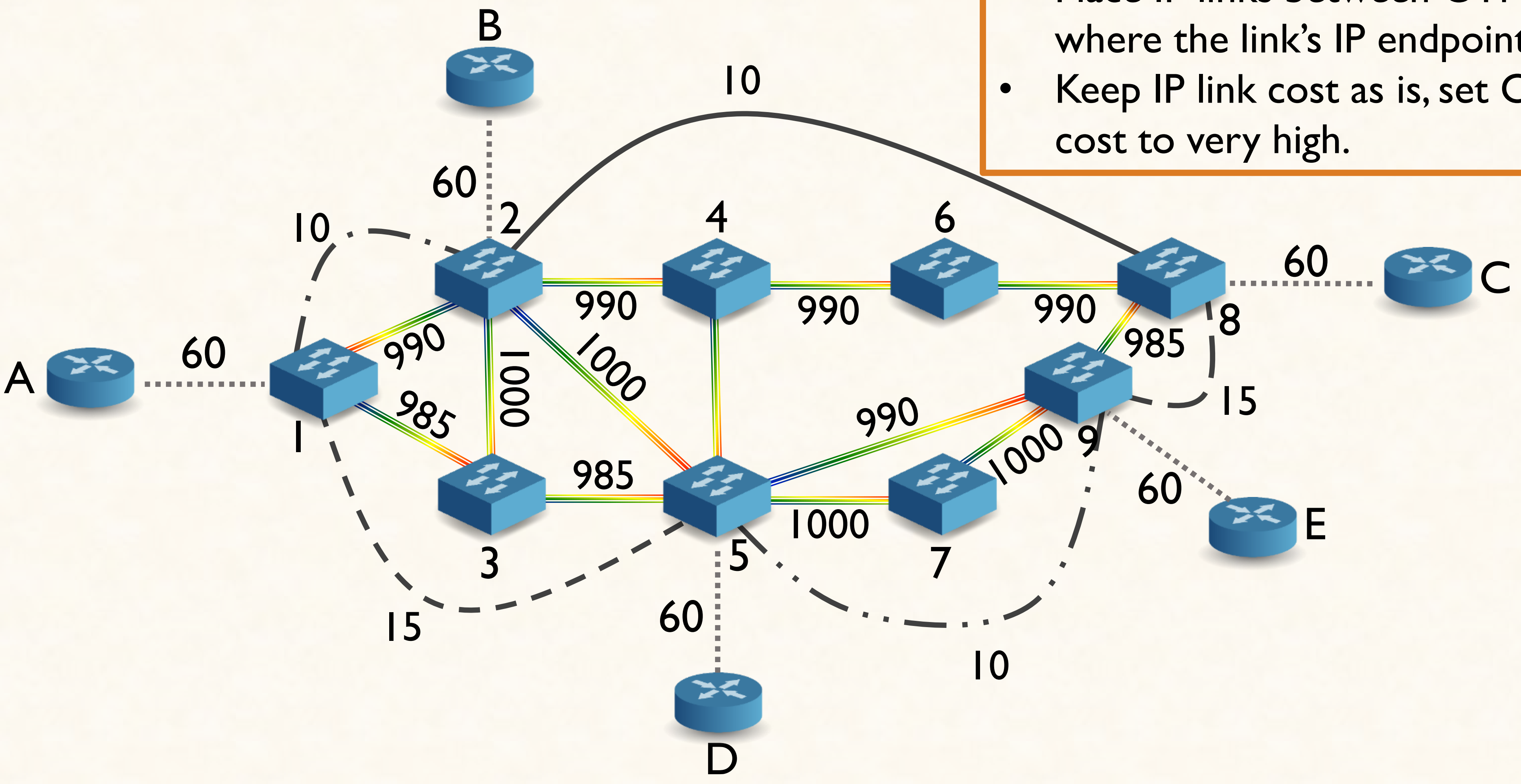


Phase-I: Collapse

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

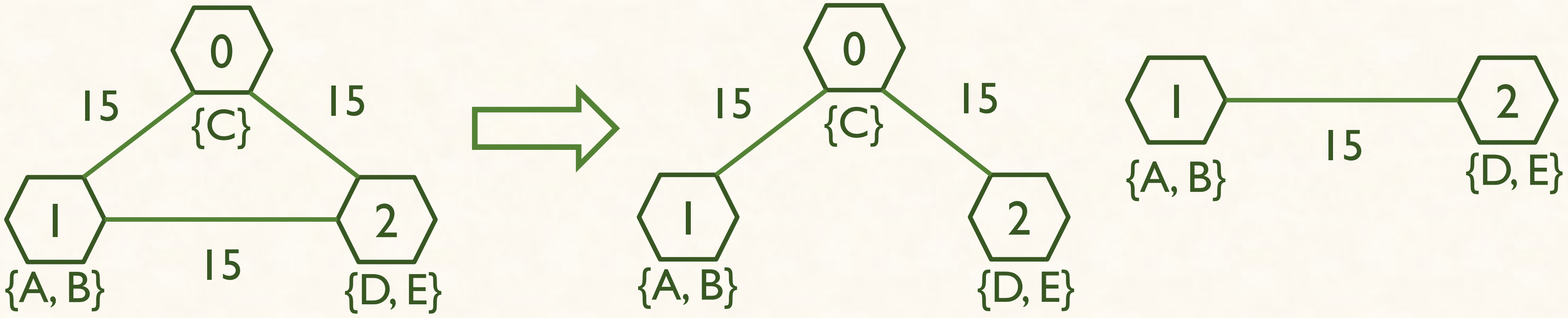


- Place IP links between OTN nodes where the link's IP endpoints are.
- Keep IP link cost as is, set OTN link cost to very high.

Phase-II: Extract

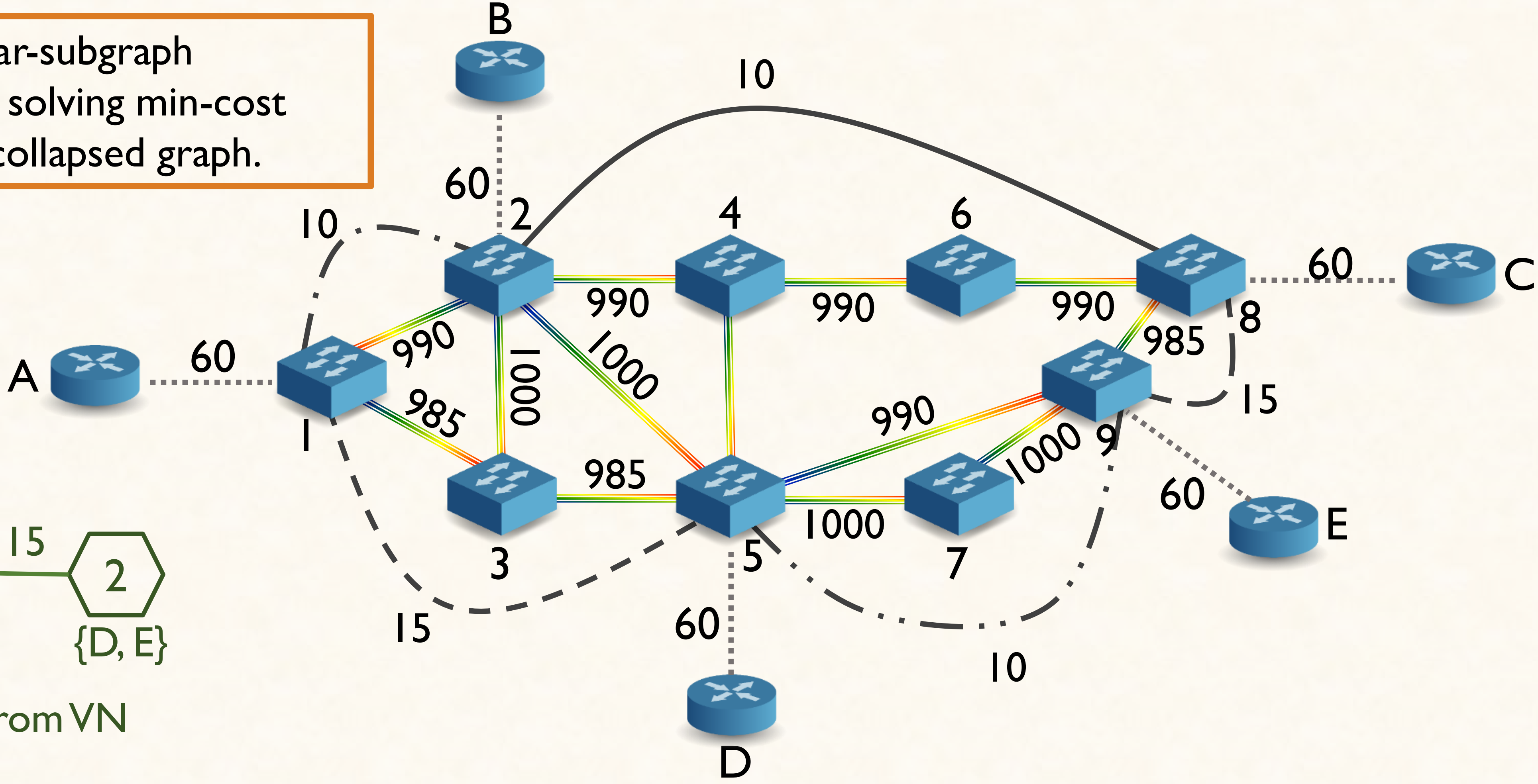
Extract star-shaped subgraph from VN

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

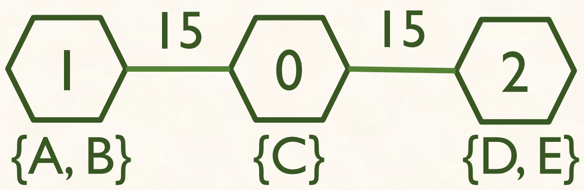


Phase – III: Embed

We reduce star-subgraph embedding to solving min-cost max-flow on collapsed graph.



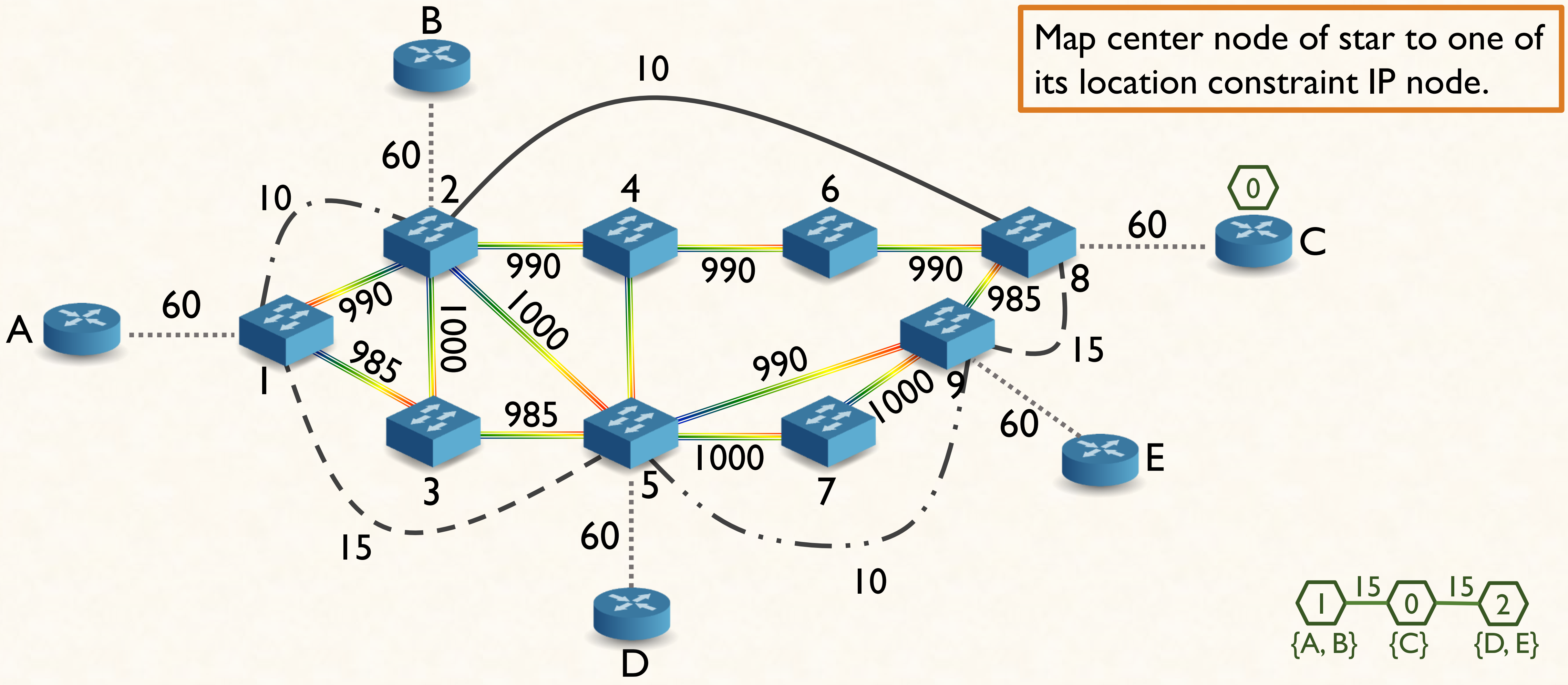
Collapsed Graph



Star subgraph from VN

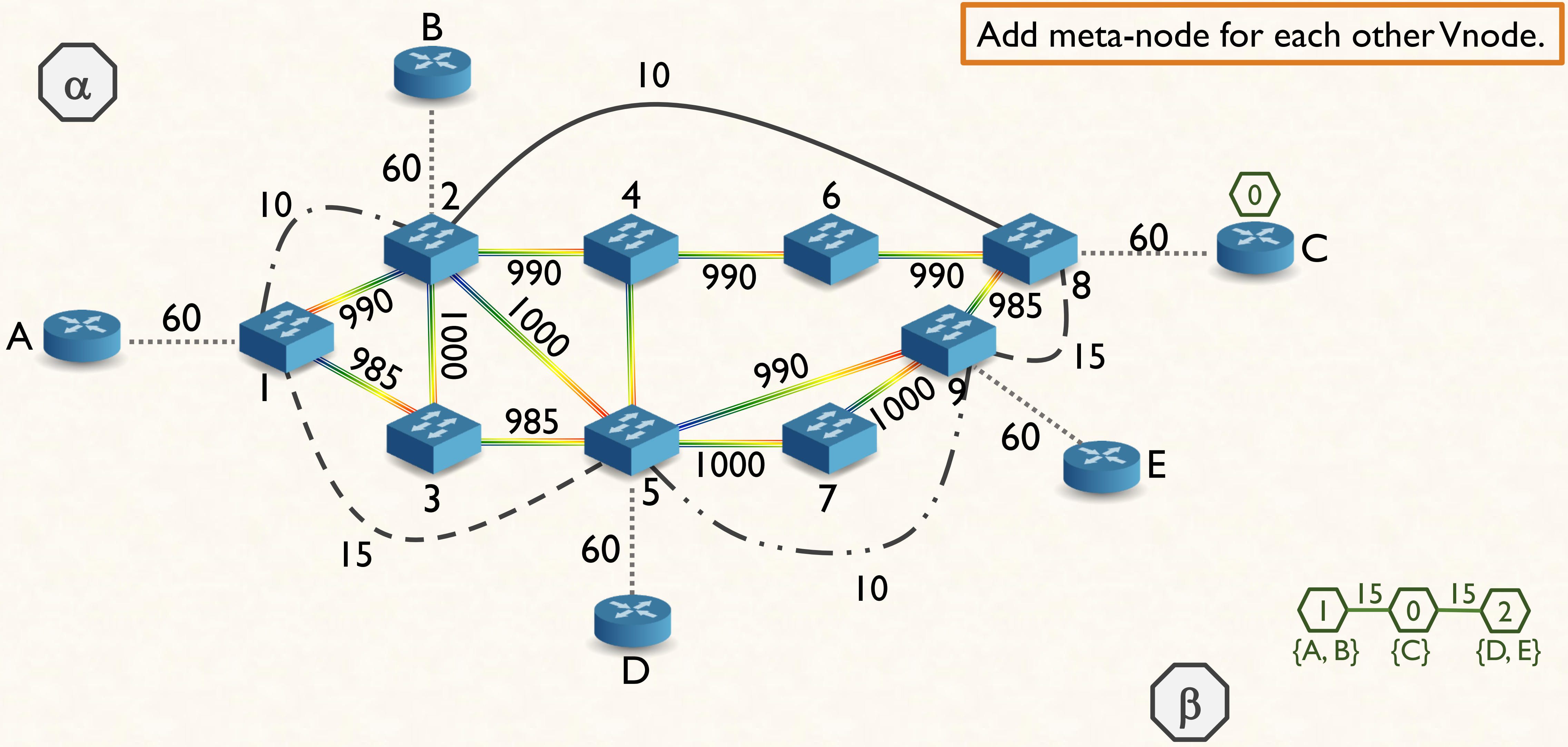
Phase – III: Embed

Map center node of star to one of its location constraint IP node.



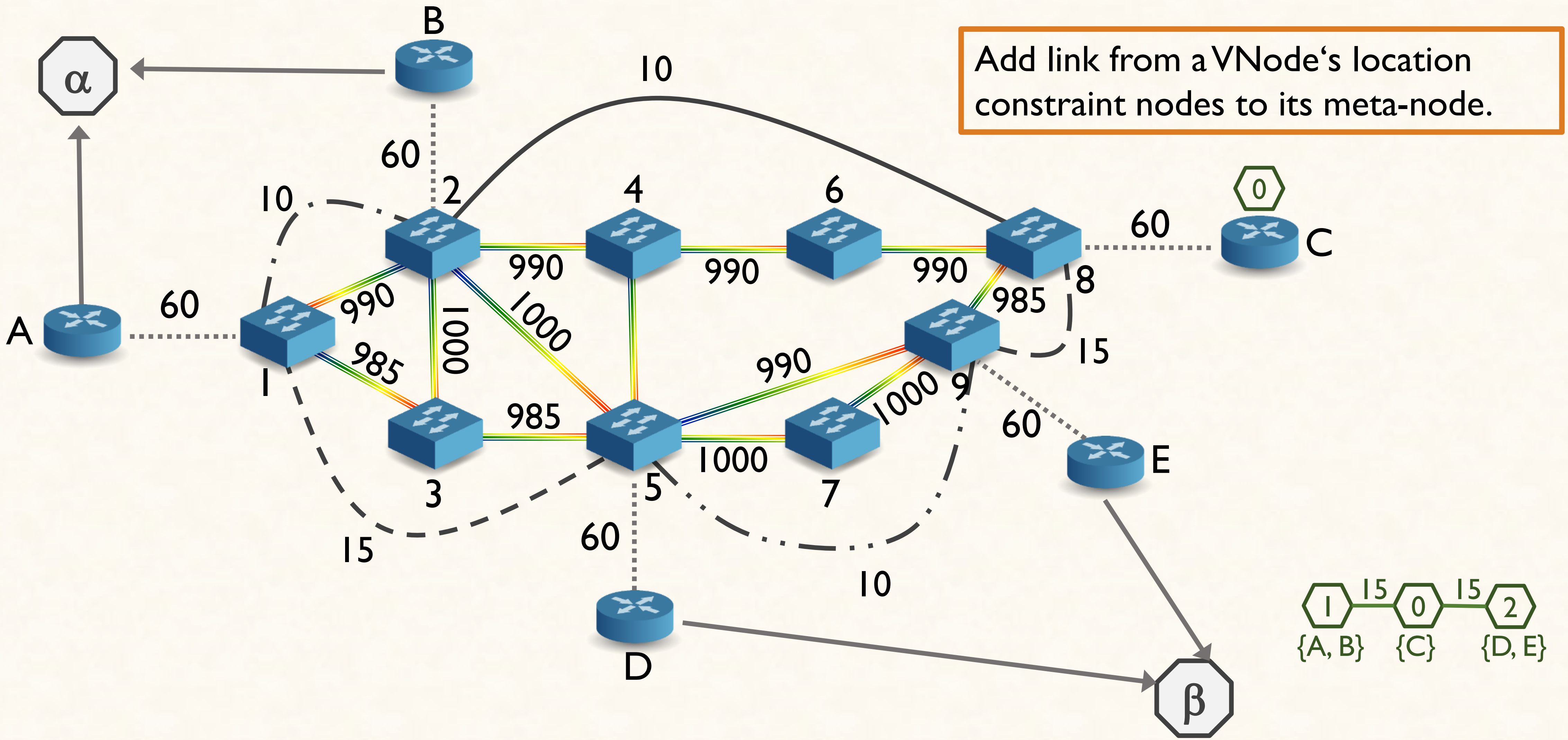
Phase-III: Embed

Add meta-node for each other Vnode.



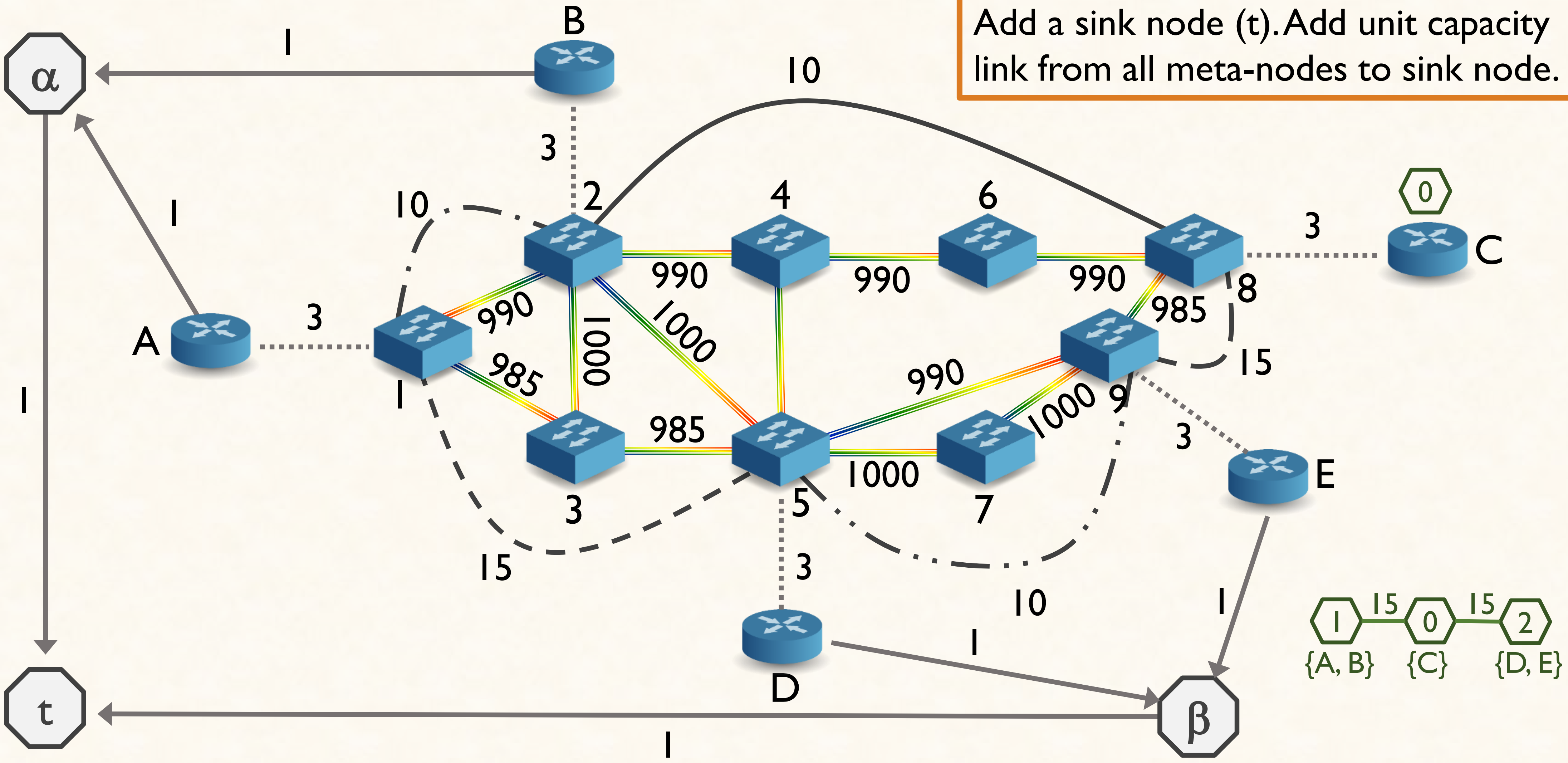
Phase-III: Embed

Add link from a VNode‘s location constraint nodes to its meta-node.



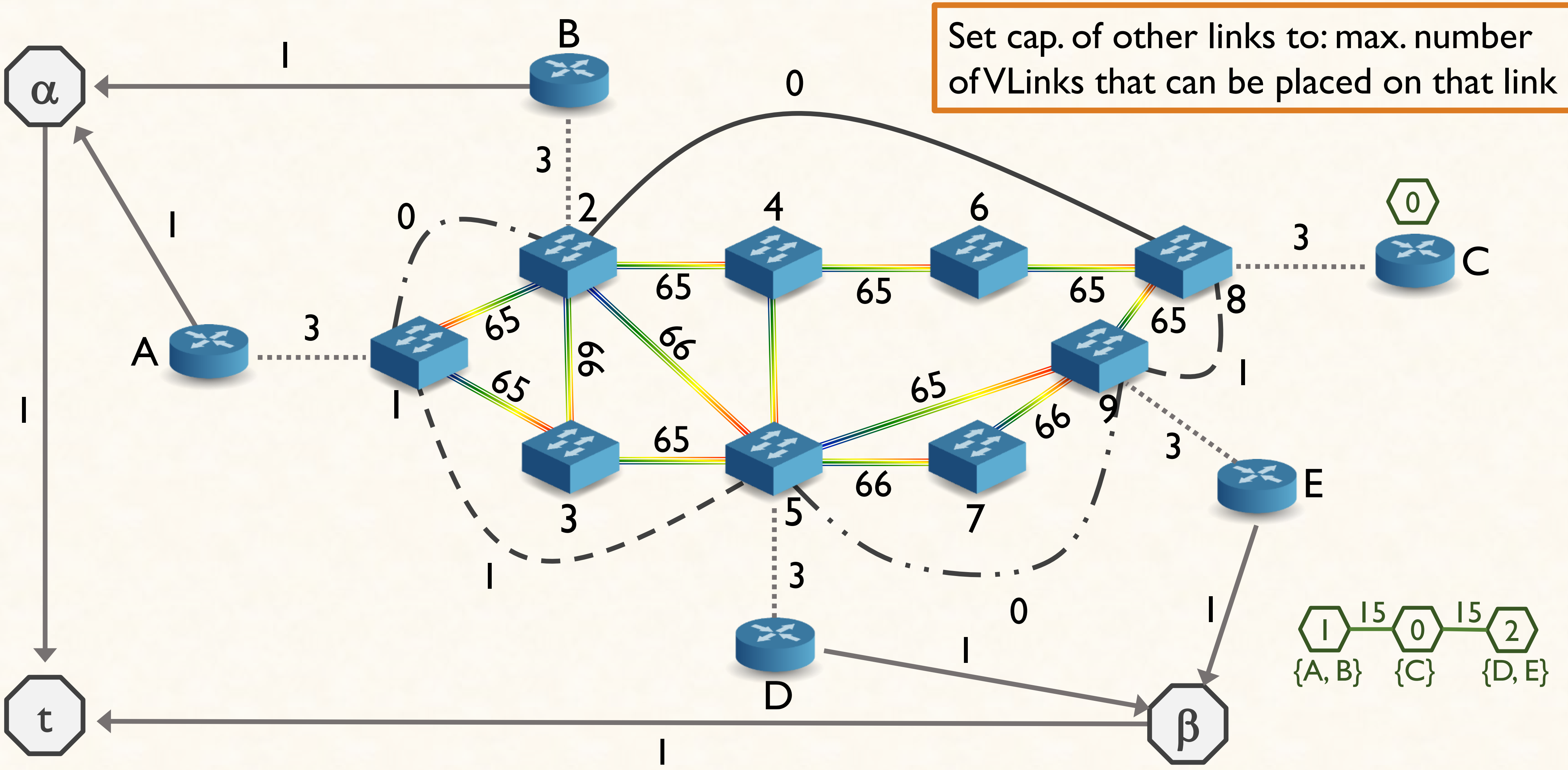
Phase-III: Embed

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



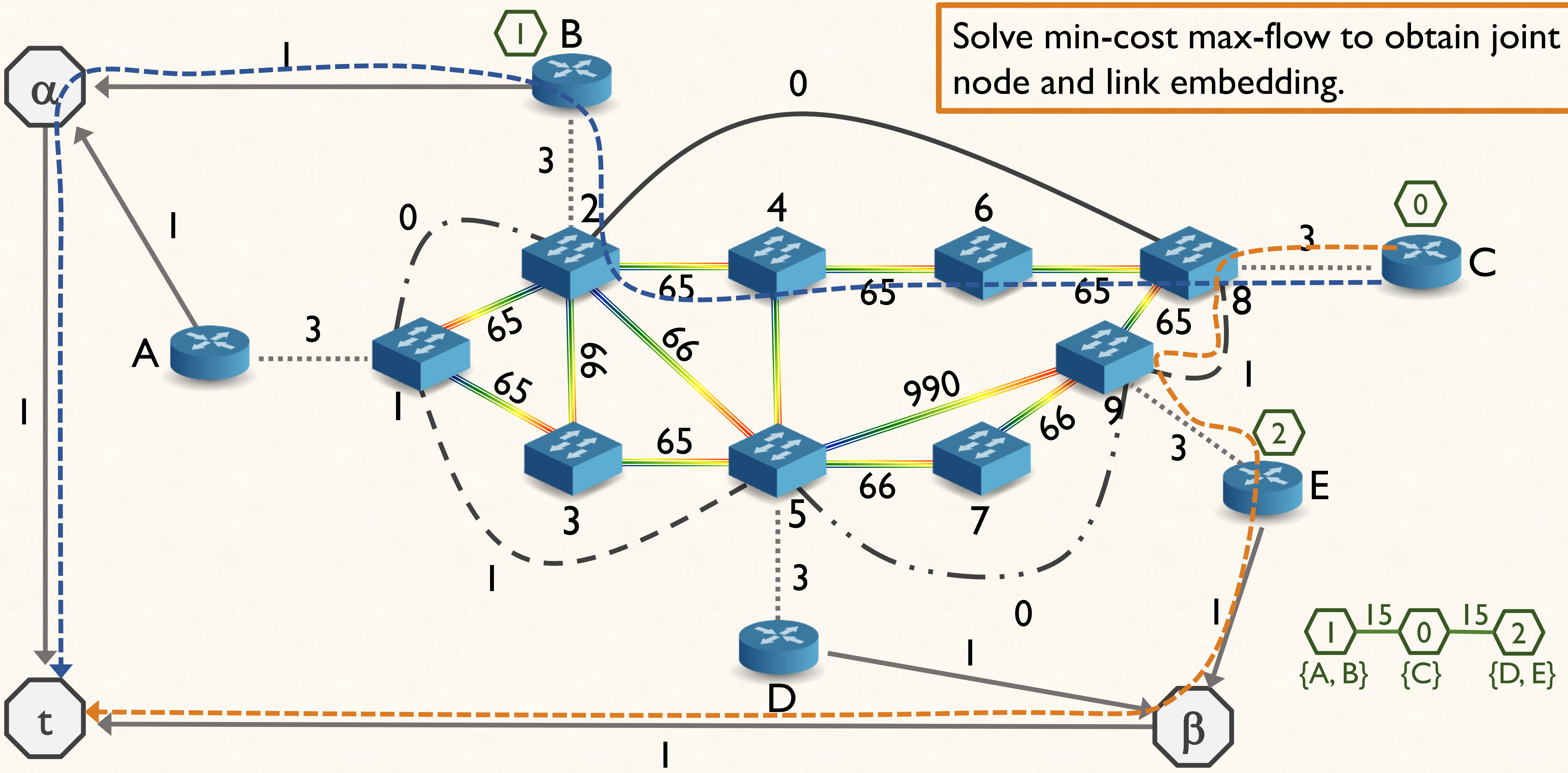
Phase-III: Embed

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

* Zhang, *et al.* "Dynamic virtual network embedding over multilayer optical networks", *Journal of Optical Communications and Networking* 7(9): 918-927, 2015.

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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67% better than D-VNE on avg.

Within ~47% of optimal 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

Summary

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

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

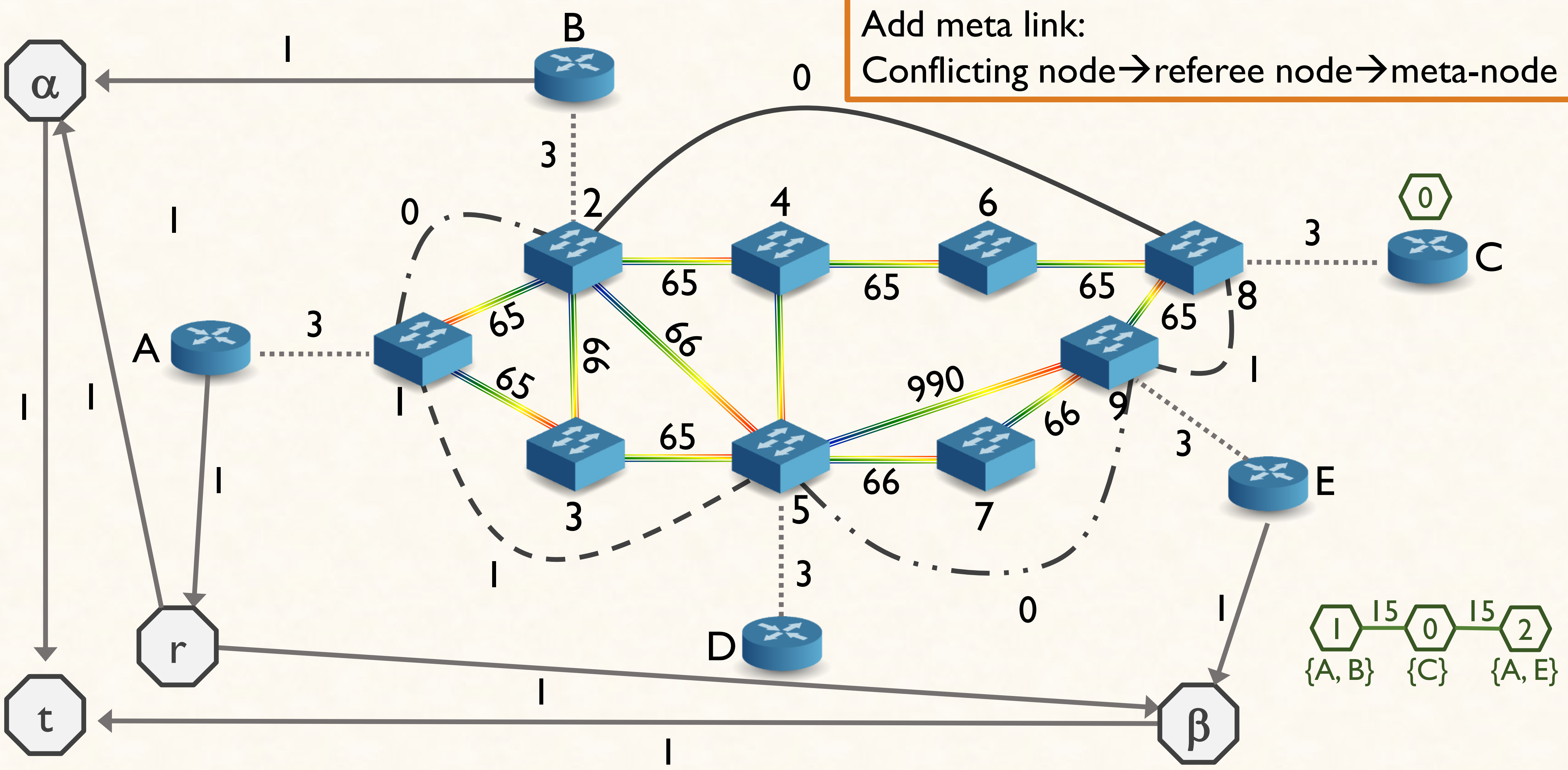
V' = Number of Virtual nodes

V = Number of nodes in collapsed graph

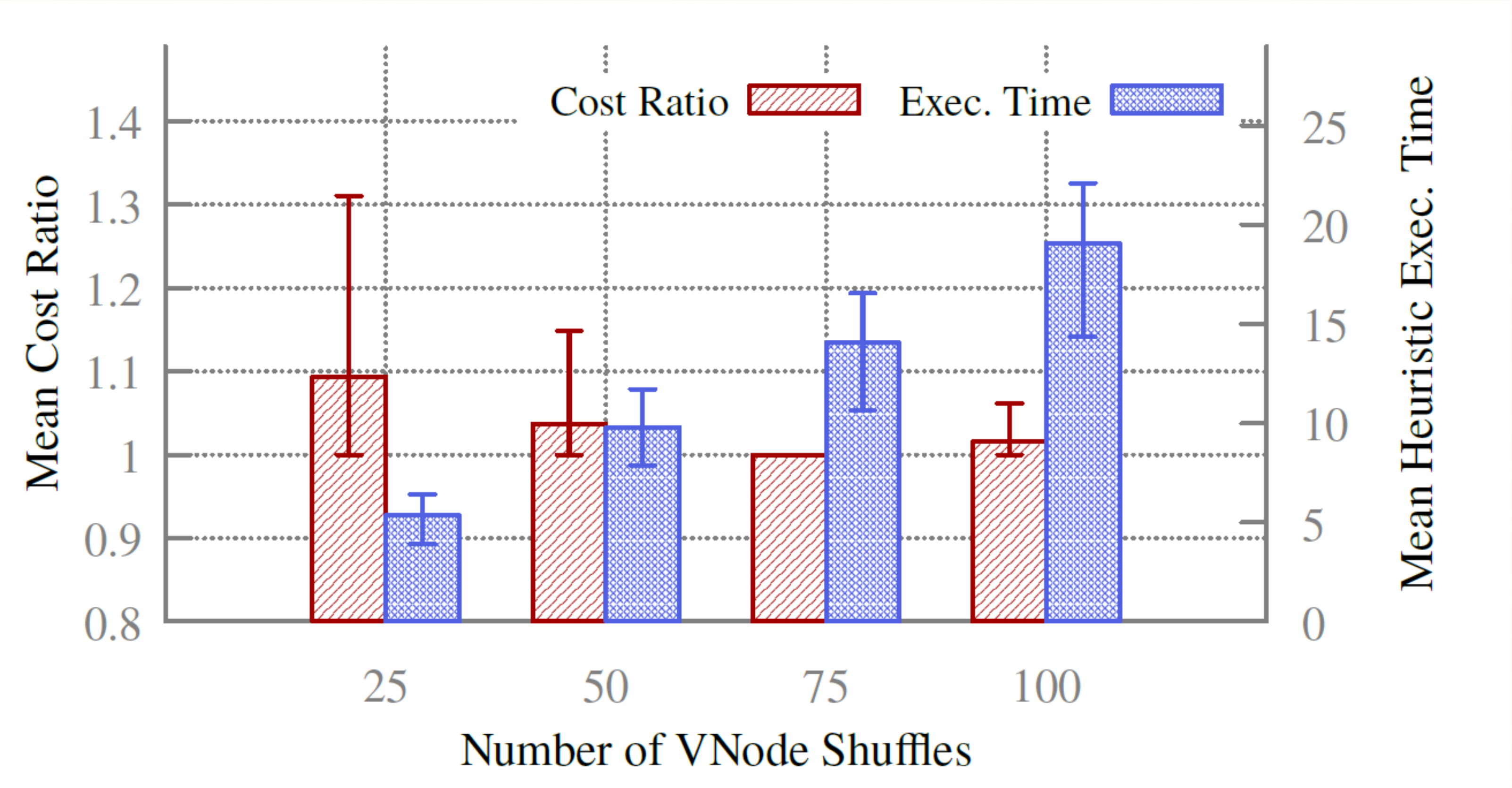
E = Number of links in collapsed graph

Conflict Resolution using "Referee Node"

Add meta link:
Conflicting node→referee node→meta-node



Impact of Virtual Node Ordering



Fixed substrate size

Why MULE?

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