Resource Management in Next Generation Communication Networks

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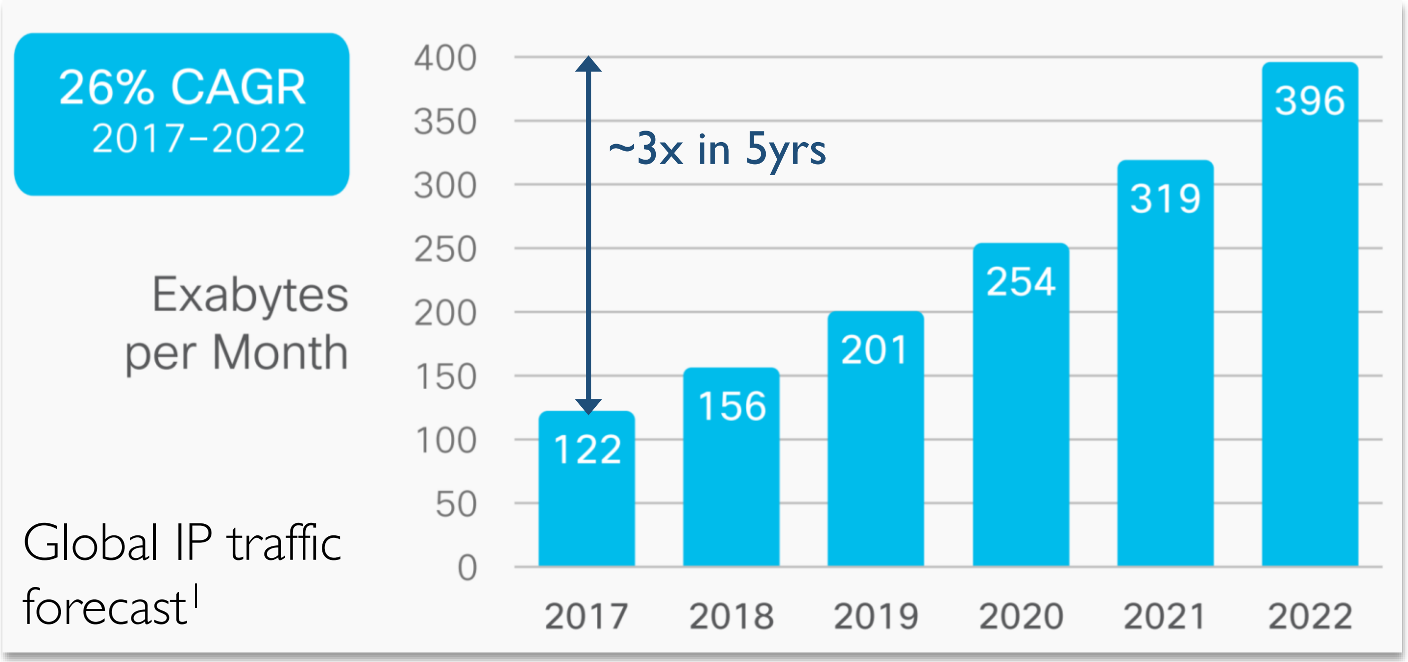
PhD Comprehensive-II Exam

University of Waterloo

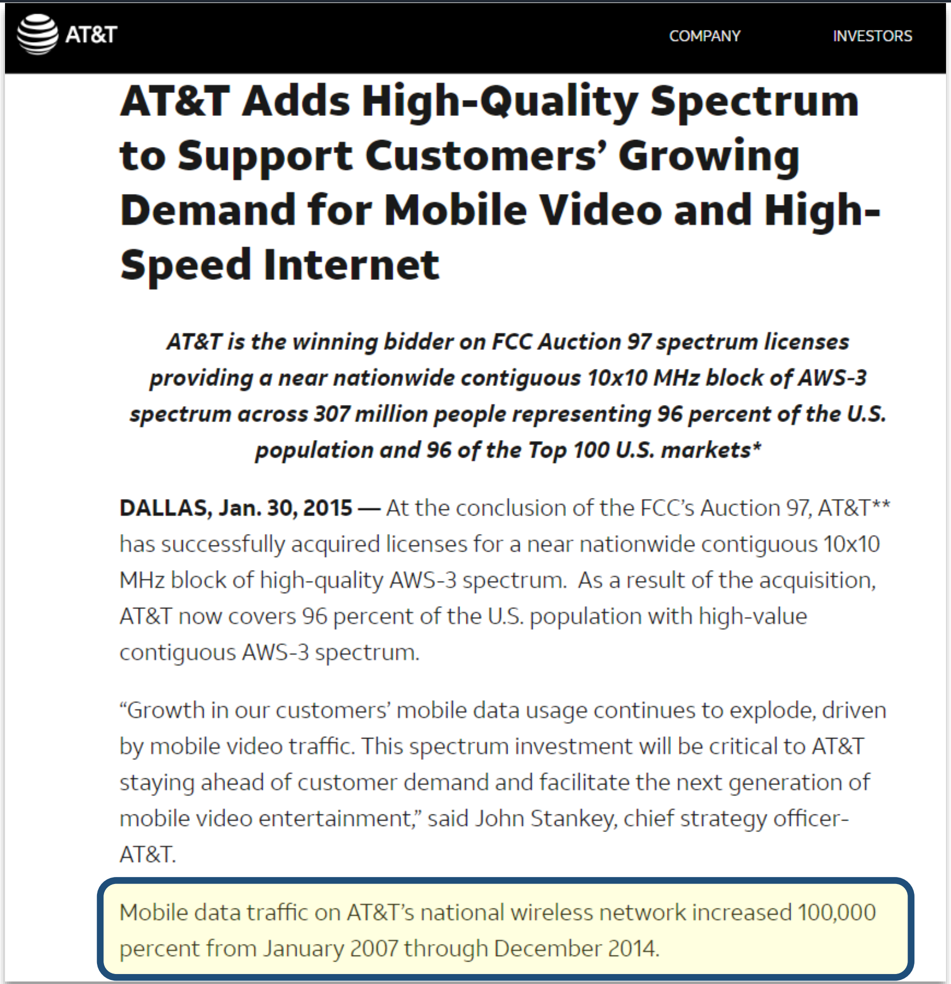
April 26, 2019

Network Management is Becoming Challenging

Network operators need to …



… scale capacity to match traffic growth



AT&T Adds High-Quality Spectrum to Support Customers' Growing Demand for Mobile Video and High-Speed Internet

AT&T is the winning bidder on FCC Auction 97 spectrum licenses providing a near nationwide contiguous 10x10 MHz block of AWS-3 spectrum across 307 million people representing 96 percent of the U.S. population and 96 of the Top 100 U.S. markets*

DALLAS, Jan. 30, 2015 — At the conclusion of the FCC's Auction 97, AT&T** has successfully acquired licenses for a near nationwide contiguous 10x10 MHz block of high-quality AWS-3 spectrum. As a result of the acquisition, AT&T now covers 96 percent of the U.S. population with high-value contiguous AWS-3 spectrum.

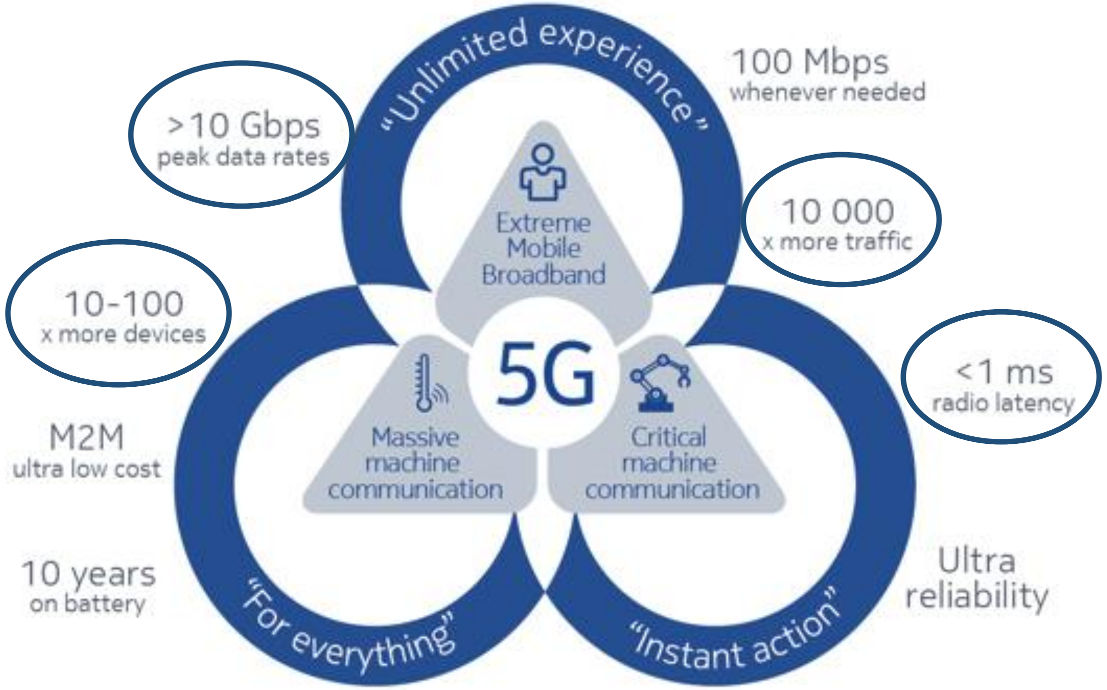
"Growth in our customers' mobile data usage continues to explode, driven by mobile video traffic. This spectrum investment will be critical to AT&T staying ahead of customer demand and facilitate the next generation of mobile video entertainment," said John Stankey, chief strategy officer-AT&T.

Mobile data traffic on AT&T's national wireless network increased 100,000 percent from January 2007 through December 2014.

[1] Cisco Visual Networking Index: Forecasts and Trends 2017 – 2022
[2] https://about.att.com/story/att_adds_high_quality_spectrum_to_support_growing_demand_for_mobile_video_and_high_speed_internet.html

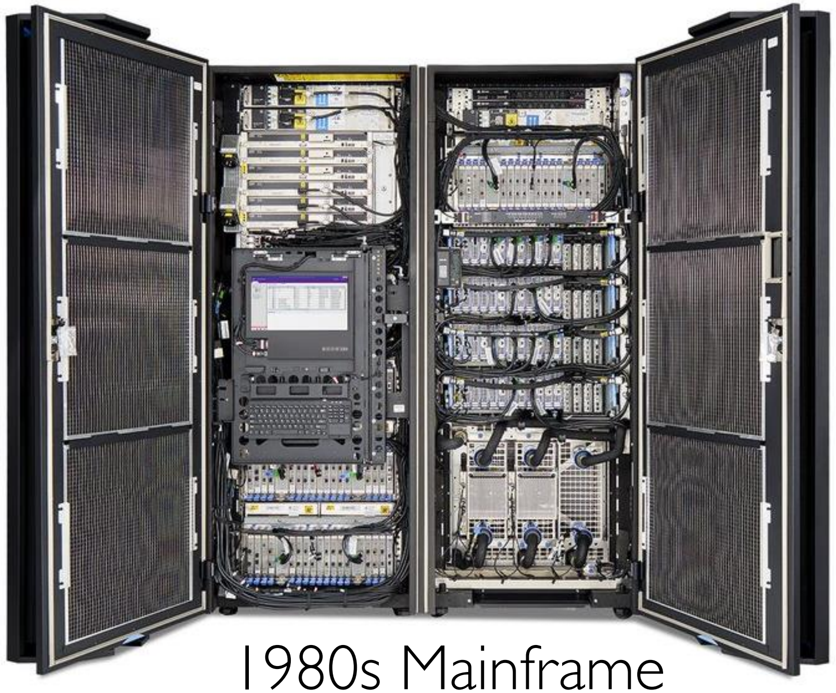
Network Management is Becoming Challenging

Network operators need to …



… satisfy diverse requirements from emerging and future applications

Networking ~~is~~ was the New Mainframe



1980s Mainframe
Proprietary;
Vertically integrated hardware/software;
Handful of vendors
Expensive; Slow innovation

2010s Networking Equipment
Proprietary;
Vertically integrated hardware/software;
Handful of vendors
Expensive; Slow innovation

Network Softwarization

App. + OS + Hardware

App.

Open API

OS

Open Instruction Set

Hardware

Network Softwarization

Specialized H/W + Network Control + Network Functions

Network control, Network Function, Service Orchestration

Open API

Commodity hardware

Three drivers of Network Softwarization

SDN

Software-Defined Networking
Separation of control from packet forwarding hardware; centralization of network control

NFV

Network Functions Virtualization
Decoupling of network functions (Firewall, NAT) from hardware middleboxes

NV

Network Virtualization
Instantiation of multiple virtual networks with different QoSs on the same physical network in isolation

Network Softwarization

Traditional networks		Next generation networks empowered by softwarization
Hardware-centric	→	Software-centric; Virtualized
CLI-driven		API-driven
Manually provisioned		Programmable
One-size-fits-all		Sliceable to meet different QoS

Fine-grained and programmable control over network resources

Reaping full benefits of softwarization requires mechanisms for efficient resource management

Thesis Proposal

Challenge some of the existing practices of resource allocation and monitoring in networks empowered by softwarization

- **NFV** Re-architecting Virtual Network Functions (VNFs) for finer-grained resource-allocation and scaling
- **NV** Resource efficient Virtual Network (VN) embedding in Multi-layer IP-over-Optical Networks
- **SDN** Software-Defined Network Monitoring

Re-architecting VNFs for Finer-grained Resource Allocation and Scaling

Transition from middleboxes to VNFs

Purpose-built hardware middlebox*

NFs are run as VNFs on pool of (virtual) resources

Commodity computing, storage & switching equipment

Transition from middleboxes to VNFs

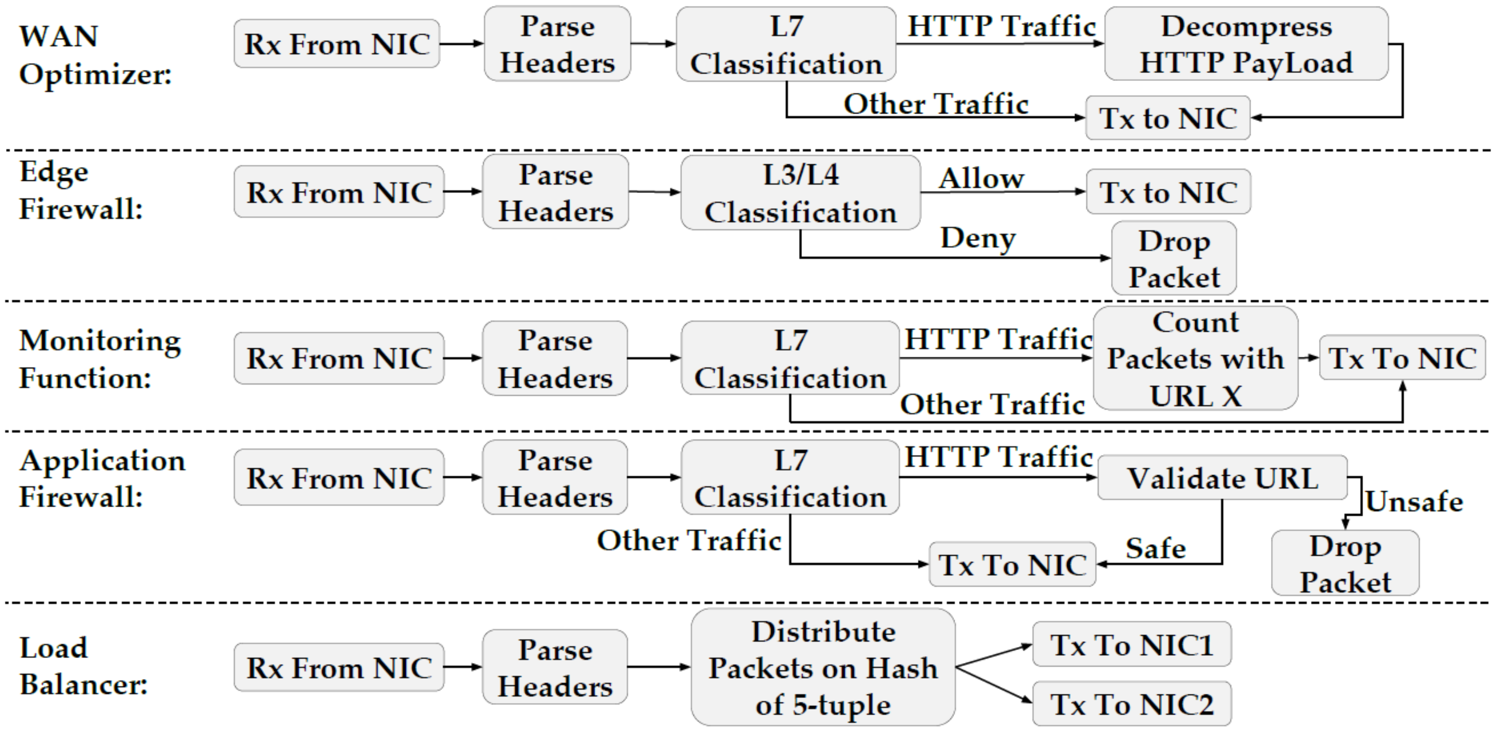
Purpose-built hardware middlebox*

NFs are run as VNFs on pool of (virtual) resources

Commodity computing, storage & switching equipment

Current practice
One-to-one substitution of middleboxes with monolithic VNFs

Monolithic VNF Limitations



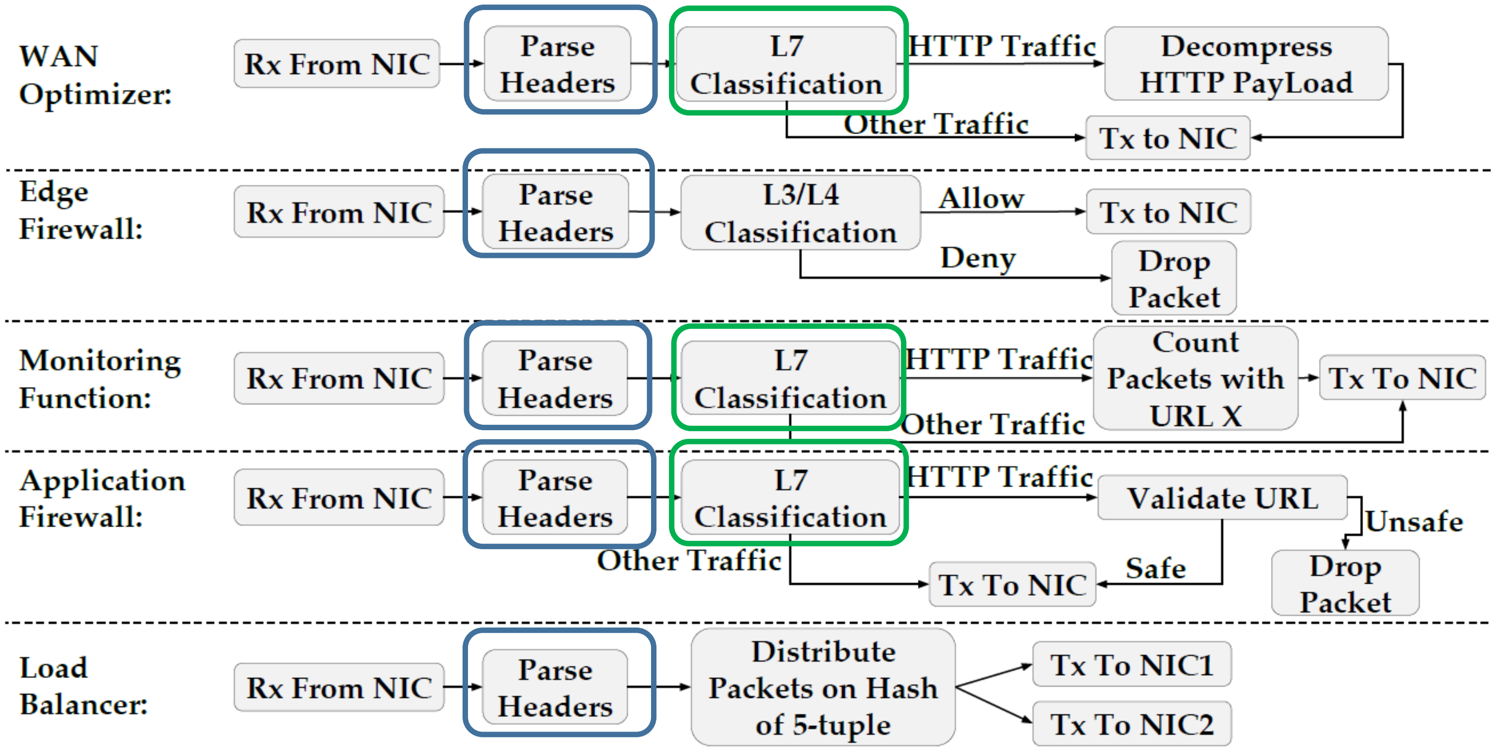
Functional decomposition of commonly found NFs in Data Centers[1]

[1]S.R. Chowdhury, *et al.* Re-architecting NFV Ecosystem with Microservices: State-of-the-art and Research Challenges. IEEE Network, April 2019

Monolithic VNF Limitations

Redundant development of common tasks (1)

Coarse-grained resource allocation & scaling (2)



Functional decomposition of commonly found NFs in Data Centers[1]

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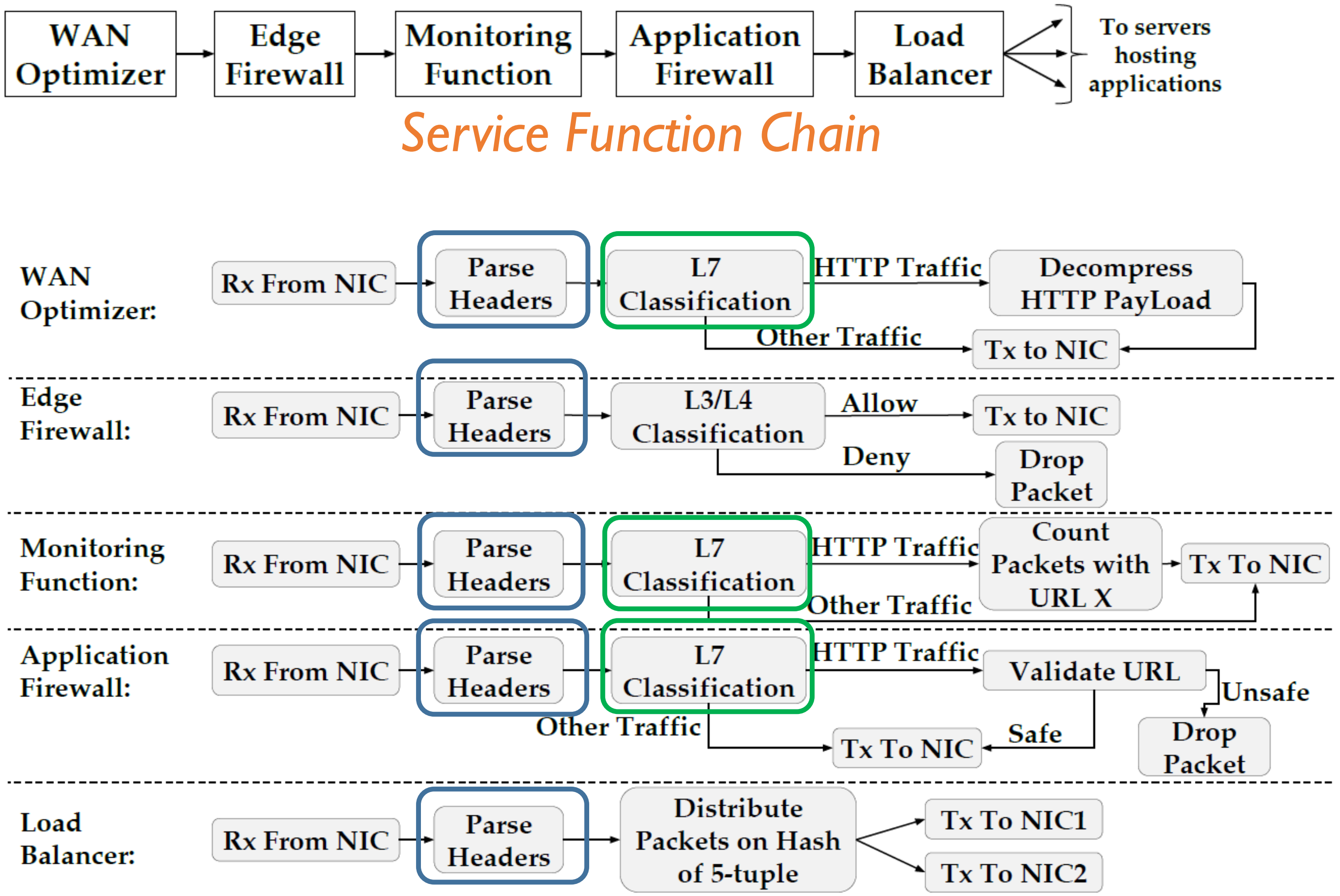
Monolithic VNF Limitations

Redundant development of common tasks 1

Coarse-grained resource allocation & scaling 2

Wasted CPU cycles when VNFs are chained 3



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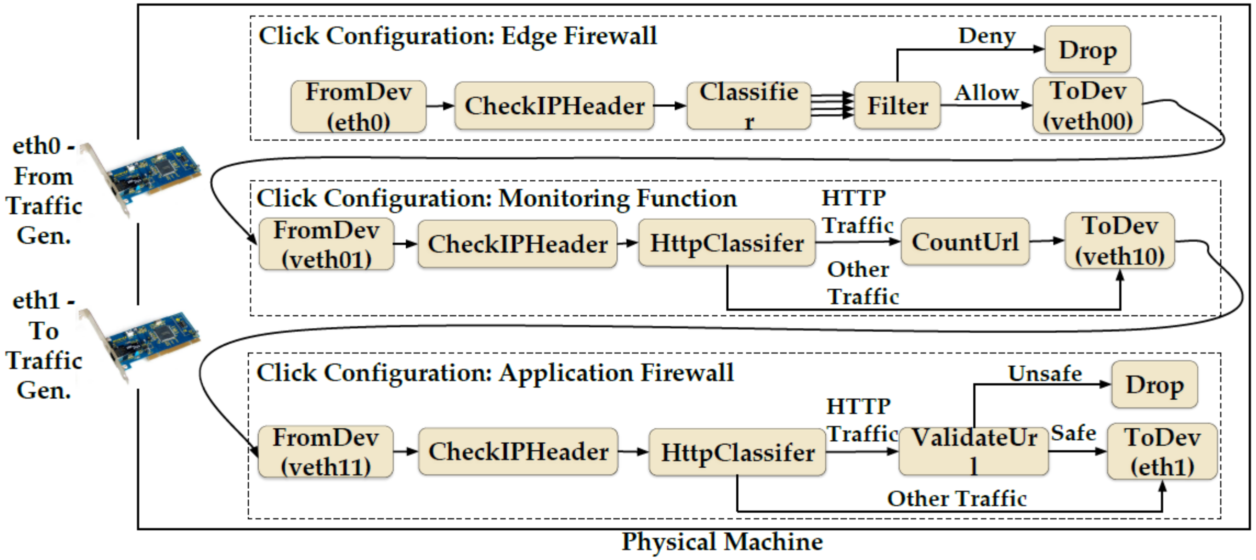
Monolithic VNFs: Impact on CPU usage

<u>Chain</u>

Edge Fw. →Monitoring → App. Fw

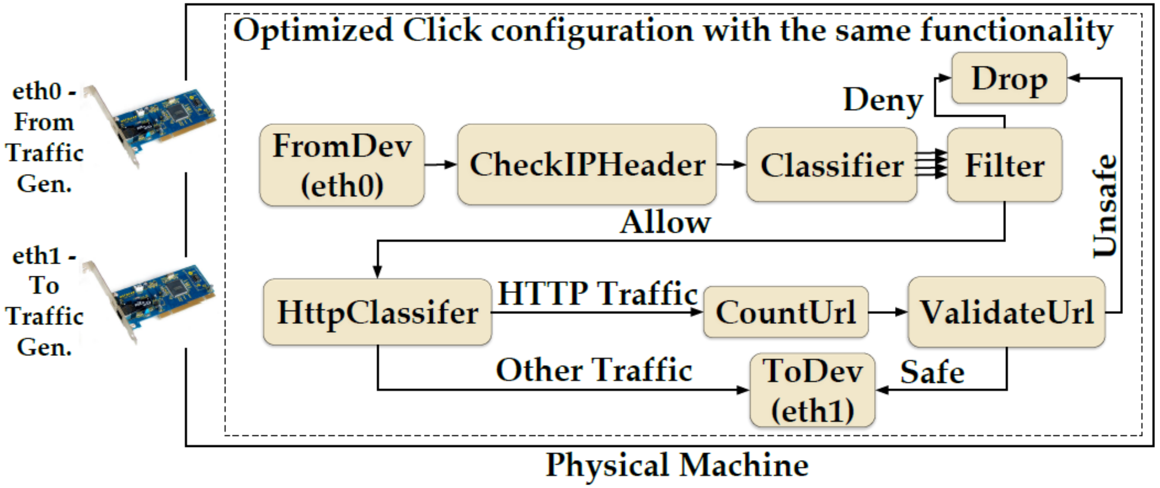
(config-i)Click-based monolithic VNFs chained with veth pairs →



<u>Traffic</u>

HTTP trace derived from a web-service (~15k hits/mo)

(config-ii) Optimized Click pipeline →



Monolithic VNFs: Impact on CPU usage

Click Element	CPU Cycles/packet saved in config-ii	Element weight in config-i
FromDevice	71.9%	0.22%
ToDevice	67.1%	0.25%
CheckIPHeader	65.1%	0.44%
HTTPClassifier	48.28%	47.8%
Overall	29.5%	-

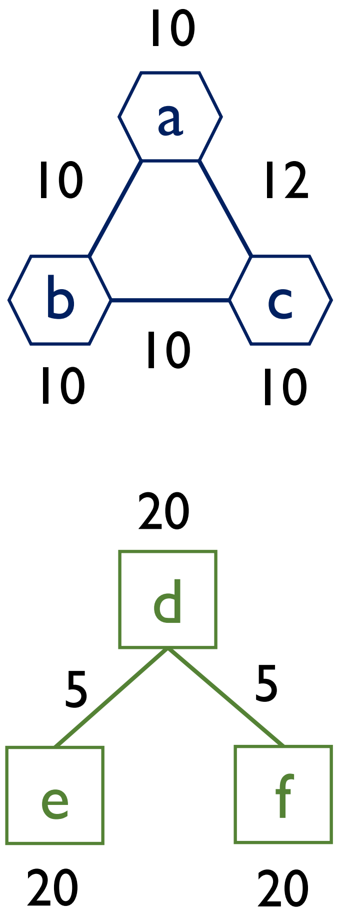
How can we engineer VNFs to better consolidate functions on the same hardware, enabling finer-grained resource allocation while maintaining the same level of performance as the state-of-the-art approaches?

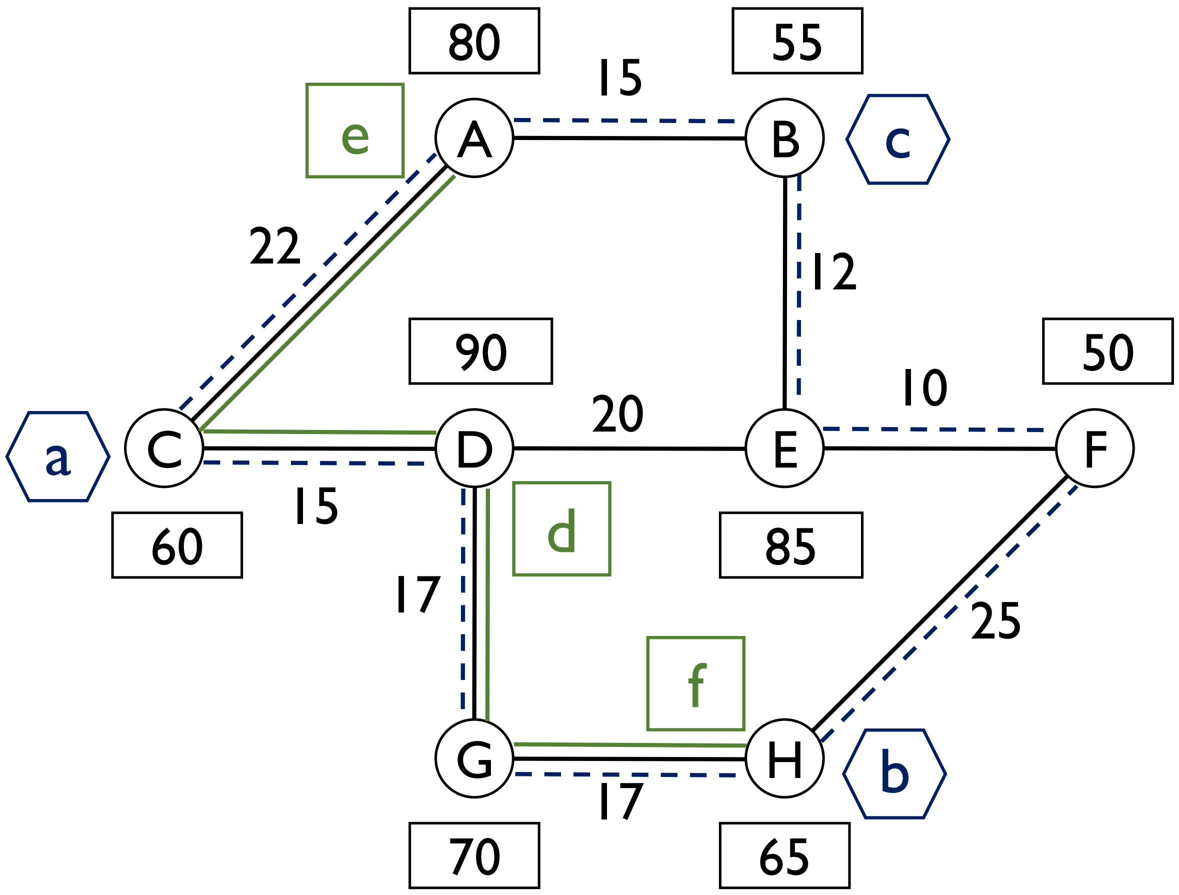
How can we engineer VNFs to better consolidate functions on the same hardware, enabling finer-grained resource allocation while maintaining the same level of performance as the state-of-the-art approaches?

Microservices approach: Decompose VNFs into independently deployable, loosely-coupled, packet processing entities.

Resource Efficient VN Embedding in Multi-layer IP-over-Optical Networks

Virtual Network Embedding (VNE)





network virtualization

About 282,000 results (**0.04** sec)

[HTML] A survey of **network virtualization**
NMMK Chowdhury, R Boutaba - Computer Networks, 2010 - El
Due to the existence of multiple stakeholders with conflicting go
to the existing Internet architecture are now limited to simple inc
deployment of any new, radically different technology is next to
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[PDF] Flowvisor: A **network virtualization** layer
R Sherwood, G Gibb, KK Yap… - OpenFlow Switch …, 2009 -
Network virtualization has long been a goal of of the **network**
multiple isolated logical networks each with potentially different
mechanisms can share the same physical infrastructure. Typica
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Network virtualization: state of the art and rese
NMMK Chowdhury, R Boutaba - IEEE Communications …, 200
Recently network virtualization has been pushed forward by its
solution to the gradual ossification problem faced by the existin
an integral part of the next-generation networking paradigm. By
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[HTML] Optimizing **network virtualization** in Xen
A Menon, AL Cox, W Zwaenepoel - USENIX Annual Technical
In this paper, we propose and evaluate three techniques for opt
in the Xen virtualized environment. Our techniques retain the ba
locating device drivers in a privilegeddriver'domain with access
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virtual network embedding

About 712,000 results (**0.05** sec)

Rethinking **virtual network embedding**: substrate support for path splitting and migration
M Yu, Y Yi, J Rexford, M Chiang - ACM SIGCOMM Computer …, 2008 - dl.acm.org
Network virtualization is a powerful way to run multiple architectures or experiments simultaneously on a shared infrastructure. However, making efficient use of the underlying resources requires effective techniques for **virtual network embedding**--mapping each **virtual** …
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Virtual network embedding: A survey
A Fischer, JF Botero, MT Beck… - … Surveys & Tutorials, 2013 - ieeexplore.ieee.org
Network virtualization is recognized as an enabling technology for the future Internet. It aims to overcome the resistance of the current Internet to architectural change. Application of this technology relies on algorithms that can instantiate virtualized networks on a substrate …
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Virtual network embedding with coordinated node and link mapping
NMMK Chowdhury, MR Rahman… - IEEE INFOCOM …, 2009 - ieeexplore.ieee.org
Recently **network** virtualization has been proposed as a promising way to overcome the current ossification of the Internet by allowing multiple heterogeneous **virtual networks** (VNs) to coexist on a shared infrastructure. A major challenge in this respect is the VN **embedding** …
☆ 99 Cited by 881 Related articles All 18 versions

Vineyard: **Virtual network embedding** algorithms with coordinated node and link mapping
M Chowdhury, MR Rahman, R Boutaba - IEEE/ACM Transactions on …, 2012 - dl.acm.org
Network virtualization allows multiple heterogeneous **virtual networks** (VNs) to coexist on a shared infrastructure. Efficient mapping of **virtual** nodes and **virtual** links of a VN request onto substrate **network** resources, also known as the VN **embedding** problem, is the first step …
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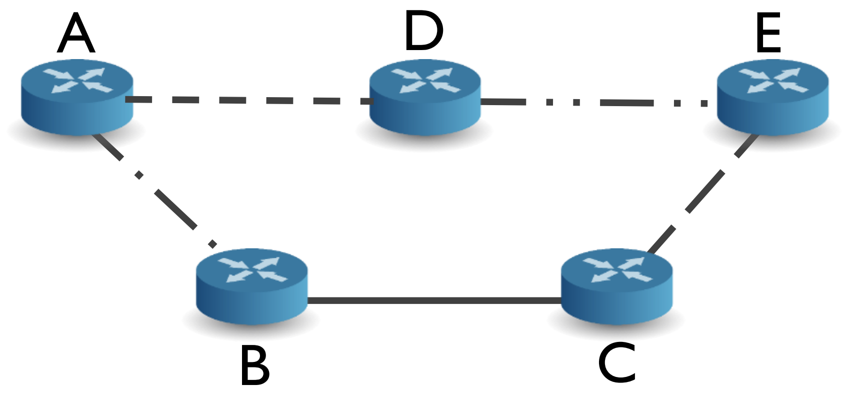
Extensive Literature, mostly focused on single-layer substrate

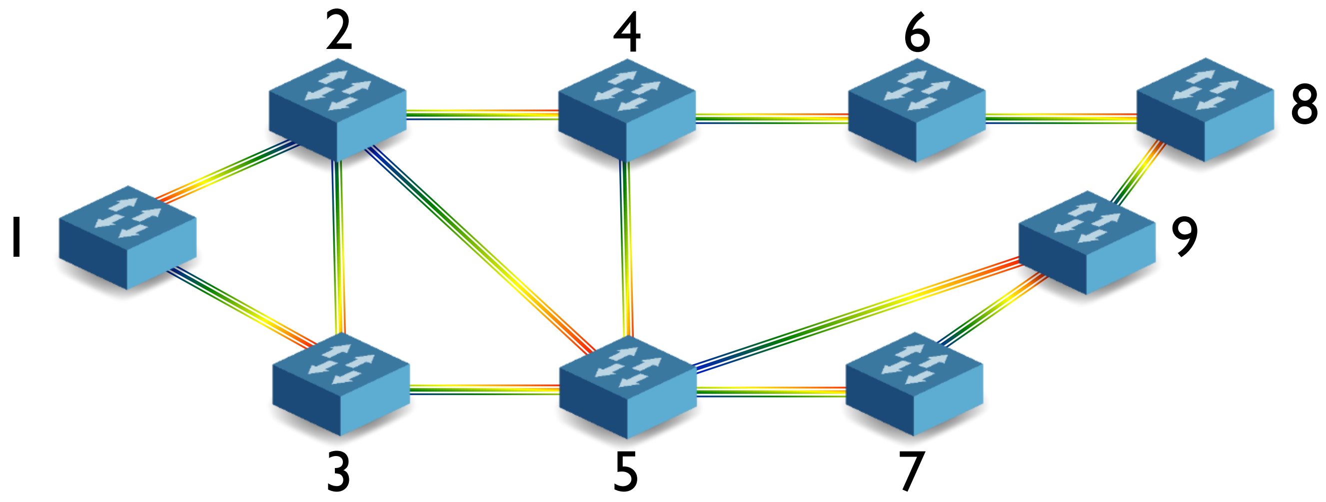
Multi-Layer IP-over-Optical Network



IP Network

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

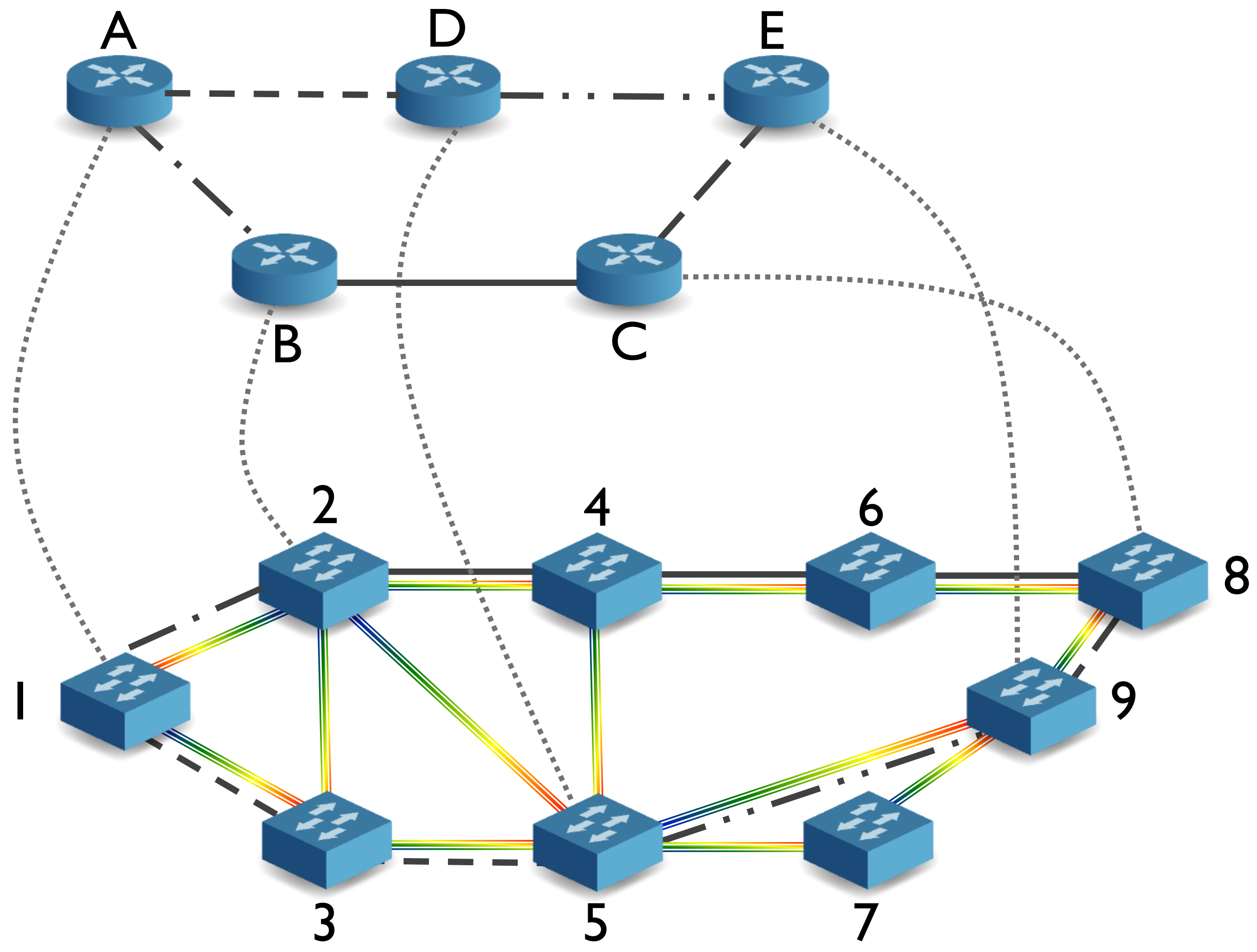
Multi-Layer IP-over-Optical Network



Optical Network

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

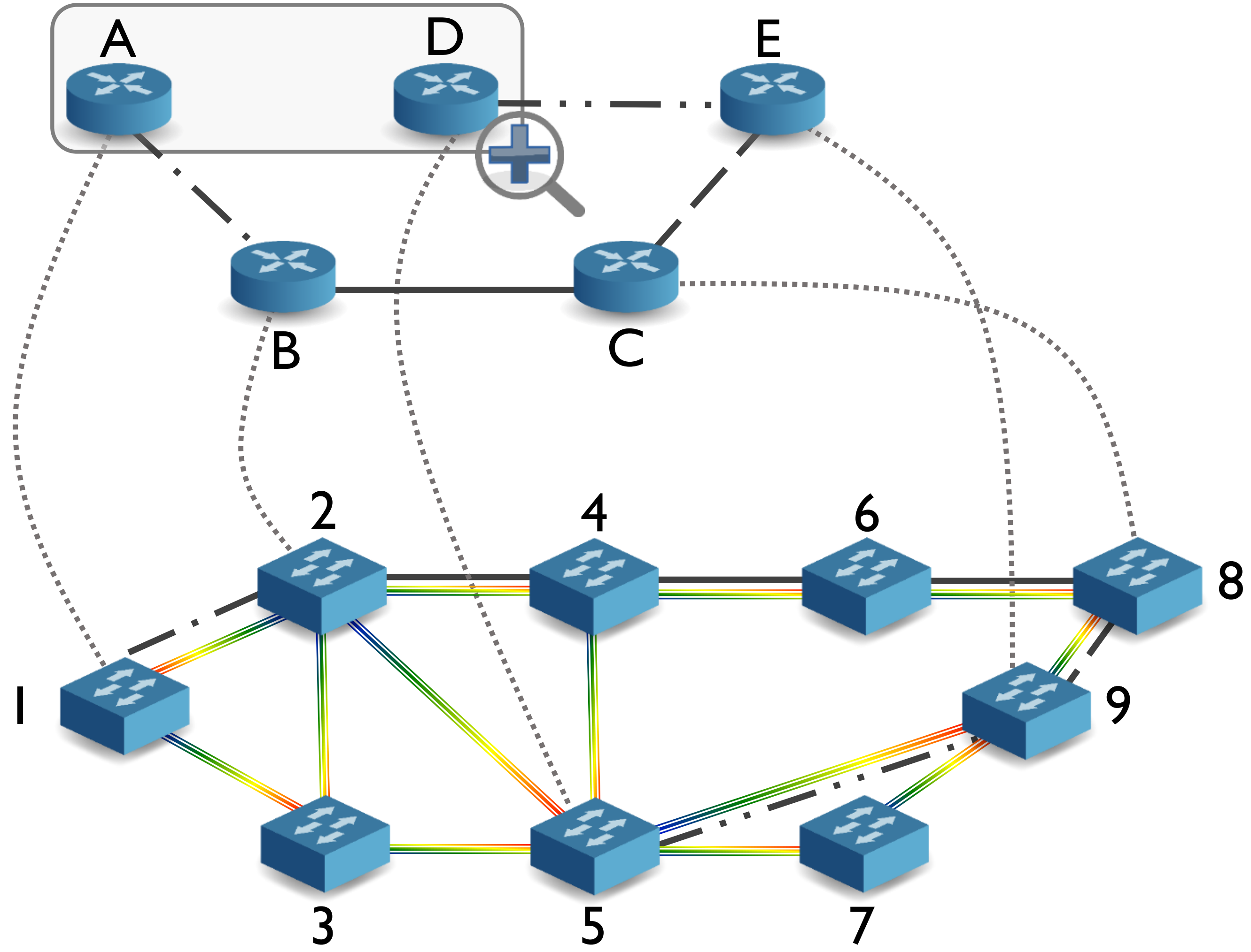
Multi-Layer IP-over-Optical Network

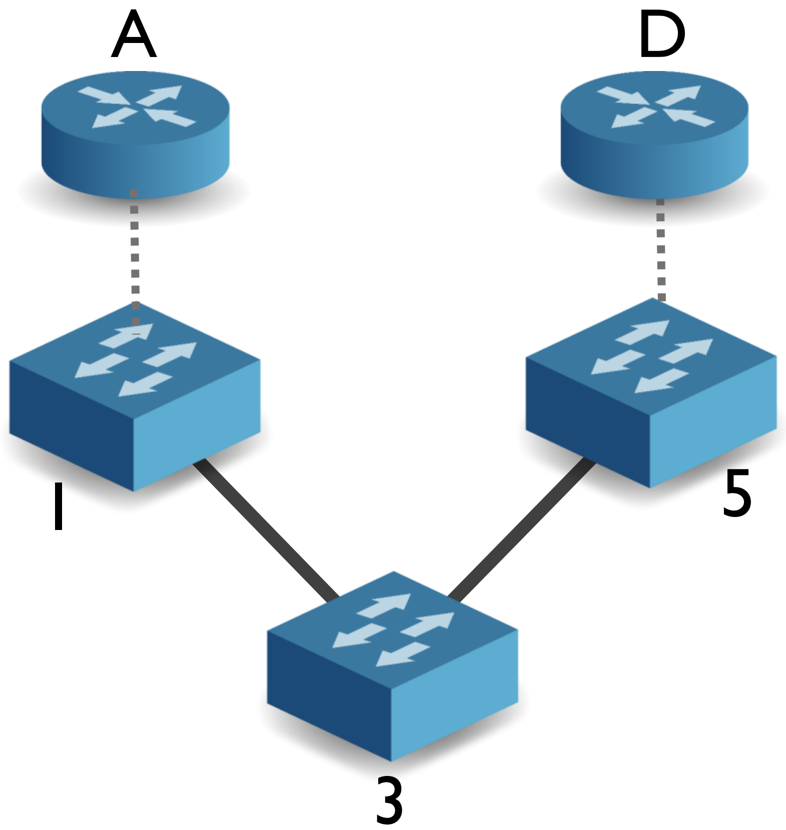


IP overlay on Optical Network

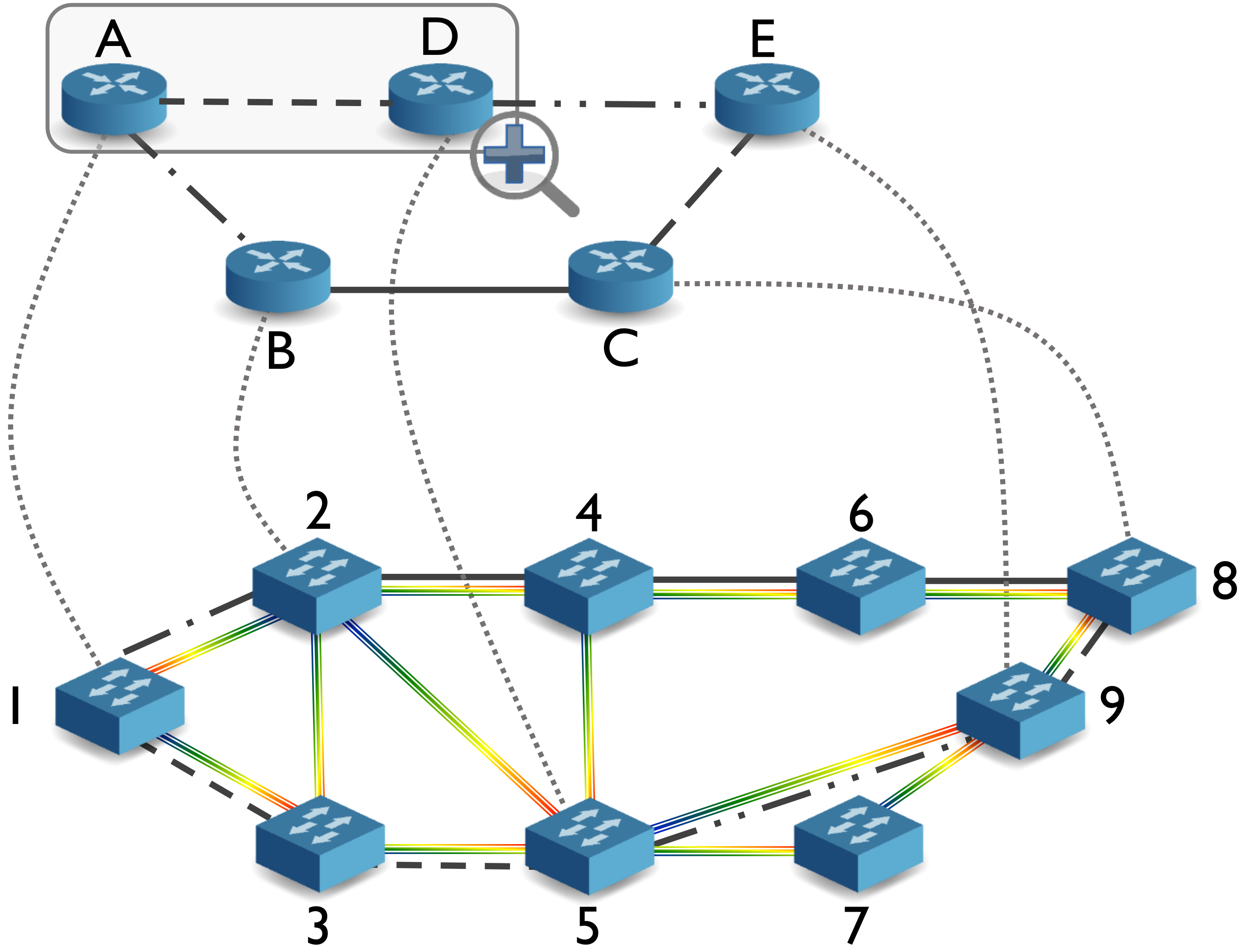
- IP routers are directly connected to optical switches
- IP links are logical and tunneled over optical paths
- Best of two worlds:
  - High capacity combined with flexible addressing, routing, traffic engineering, resource allocation.

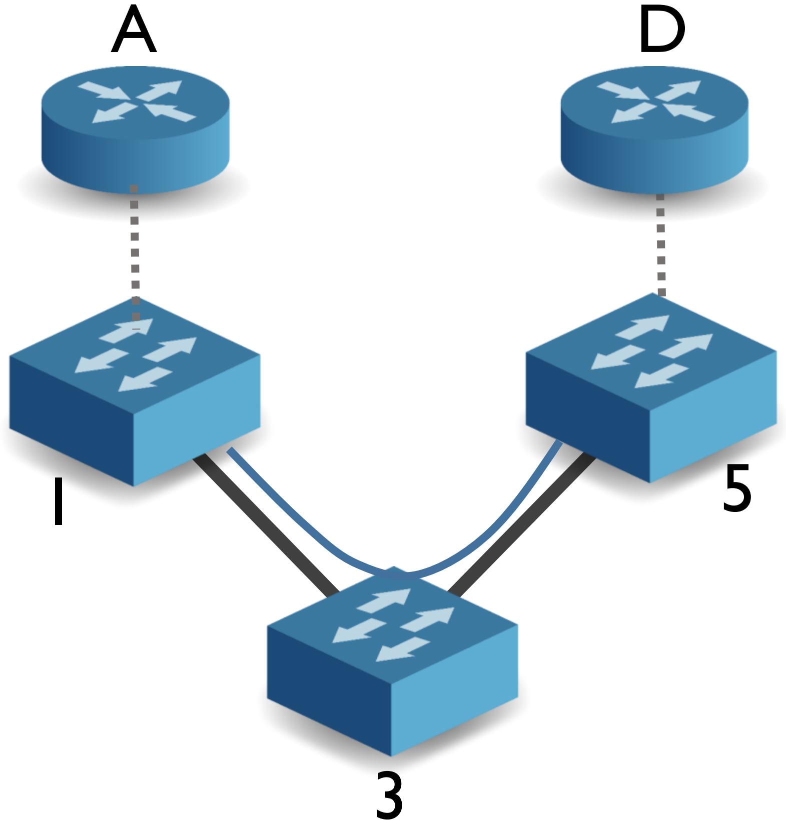
Topological Flexibility of Multi-Layer Networks





Topological Flexibility of Multi-Layer Networks





New IP Links can be created on demand

Q. How can we leverage the topological flexibility of multi-layer networks for VNE?

Q. How can we leverage the topological flexibility of multi-layer networks for VNE?

A. If the IP network does not have sufficient capacity for VNE, then we can increase capacity, by creating new IP links

The Multi-Layer VNE (MULE) Problem

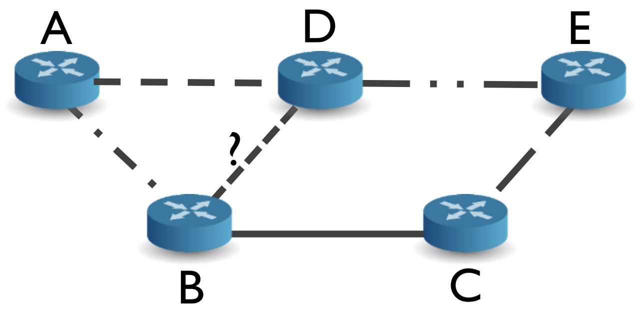
The Multi-Layer VNE (MULE) Problem

Jointly determine

The Multi-Layer VNE (MULE) Problem

Jointly determine

Creation of New IP links
(if necessary)

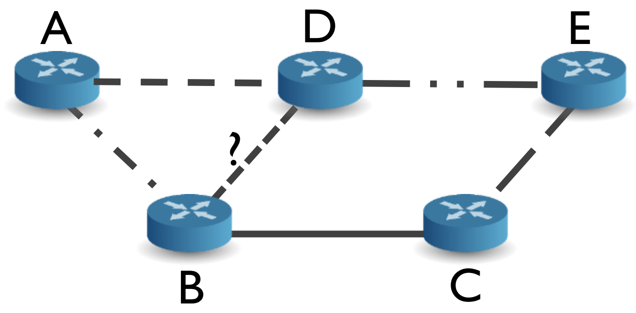


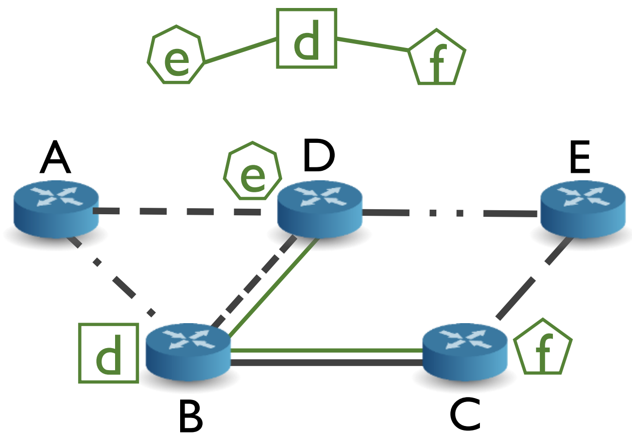
The Multi-Layer VNE (MULE) Problem

Jointly determine

Creation of New IP links (if necessary)

VN Embedding on the IP Layer

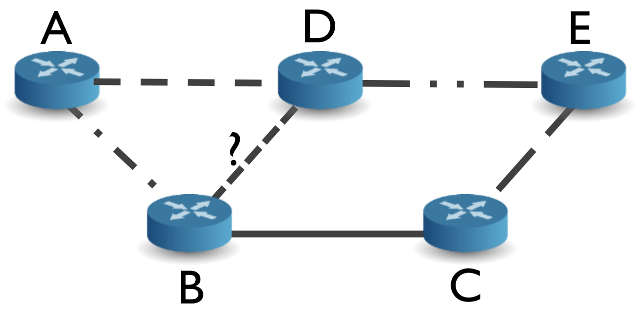


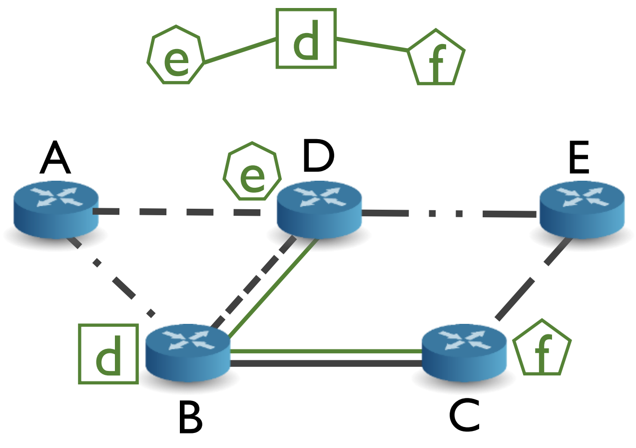


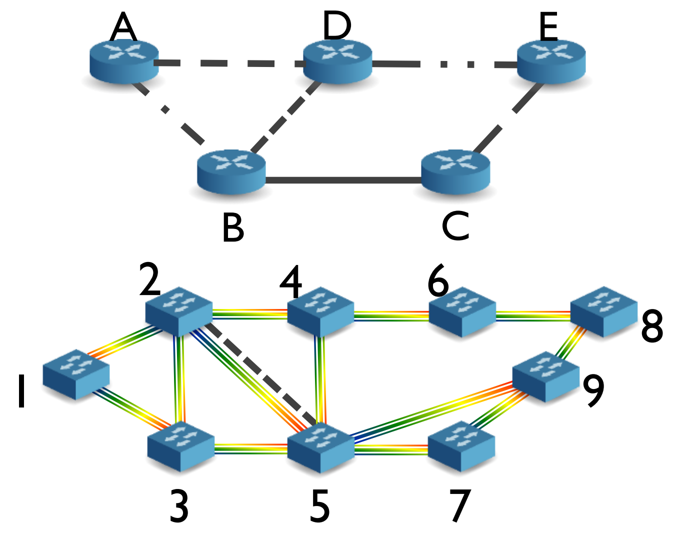
The Multi-Layer VNE (MULE) Problem

Jointly determine

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







The Multi-Layer VNE (MULE) Problem

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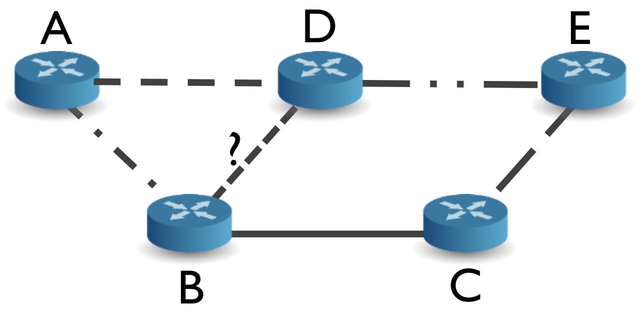
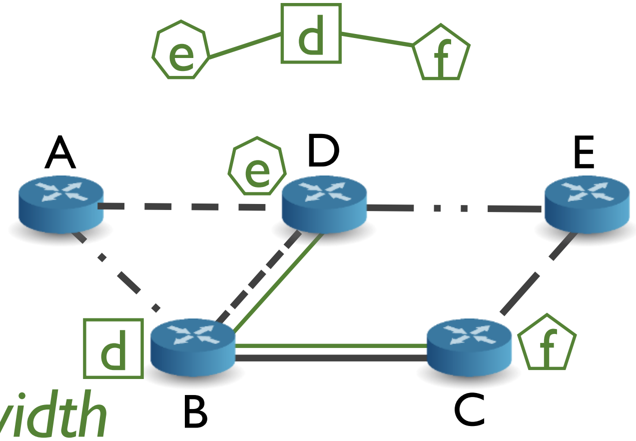
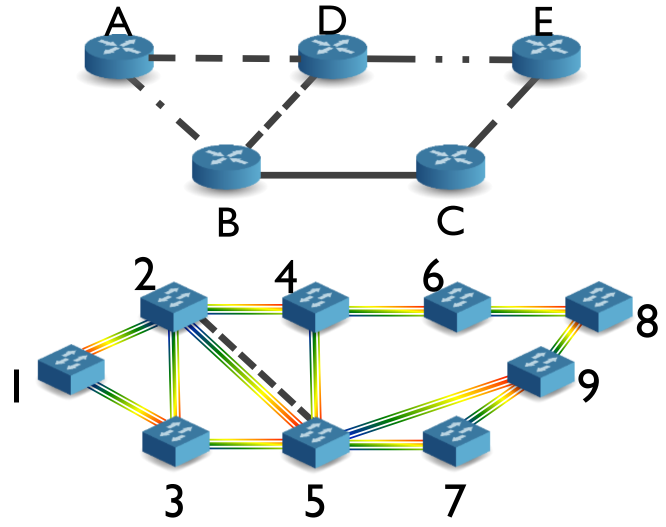






Objective: Jointly minimize bandwidth allocation cost across both layers

Progress

A suit of solutions to MULE

OPT-MULE

Integer Linear Program for Optimal Solution

(NP-hard)

FAST-MULE

Heuristic algorithm for joint virtual node and link mapping on a merged IP-Optical network

Software-Defined Network Monitoring

Background

- Monitoring is orthogonal to resource management and is fundamental to network management
- SDN's centralized control plane facilitates a single point of data collection at per-flow granularity
- State-of-the-art in programmable data-plane allows line-rate computation of complex statistics beyond simple counter-based primitives

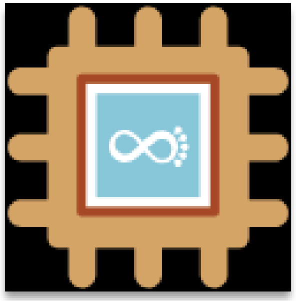
Accuracy-overhead Trade-off

	High Overhead	Low Overhead
Spatial coverage (switch, flow)	Accurate network view (monitor all flows)	Approximate network view (sample flows)
Temporal coverage (query frequency)	Captures even short-lived events (microbursts)	Misses short-lived events

(P1) Determine monitoring frequency that strikes a balance between measurement accuracy & monitoring overhead.

Resource-visibility Trade-off

Programmable switches and general purpose servers can measure complex statistics beyond simple counters in the data plane (flow size distribution, heavy hitters)



Visibility into network traffic

Resources (CPU, memory)

Resources (CPU, memory)

Visibility into network traffic

(P2) Optimally distribute monitoring tasks on end-hosts and programmable switches for maximizing network visibility while considering their resource constraints

Progress: Adaptive Flow Monitoring

- PayLess: traffic intensity-aware adaptive monitoring algorithm
  - Assign a default monitoring frequency to flows
  - If no significant traffic change, decrease frequency
  - If change in traffic is significant, increase frequency

Future Plan: Address P2

- Develop monitoring probes leveraging: programmable hardware and advances in software packet processing.
- Quantify the gains and costs of network monitoring on programmable switches and end-hosts.
- Investigate discrete optimization techniques (e.g., those used for solving facility location and its variants) for solving (P2).
- Consider exploiting the law of diminishing marginal utility for allocating resources (e.g., registers and tables in switches, memory and CPU in end-hosts) to network monitoring tasks.
- Validate through testbed deployment and experimentation using publicly available packet captures and topologies.

Questions?

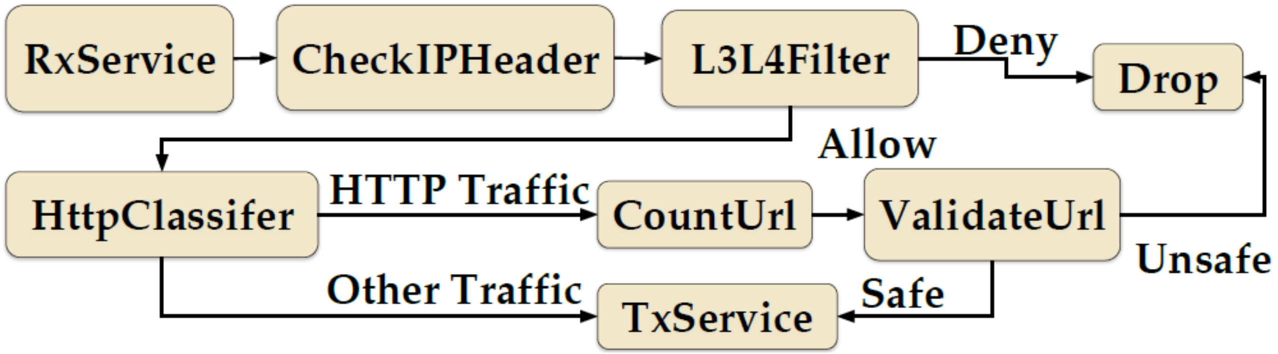
Backup

State-of-the-art

- 1999 Click [SOSP'99]: Pioneered modular packet processing in software
- 2012 CoMb [NSDI'12]: Motivated disaggregation
- 2016 OpenBox [SIGCOMM'16]: Separation of middlebox's control & data plane
- 2018 Microboxes [SIGCOMM'18]: Consolidation of TCP processing tasks
- 2019 µNF [NetSoft'19]: S/W architecture & optimizations for disaggregated VNFs

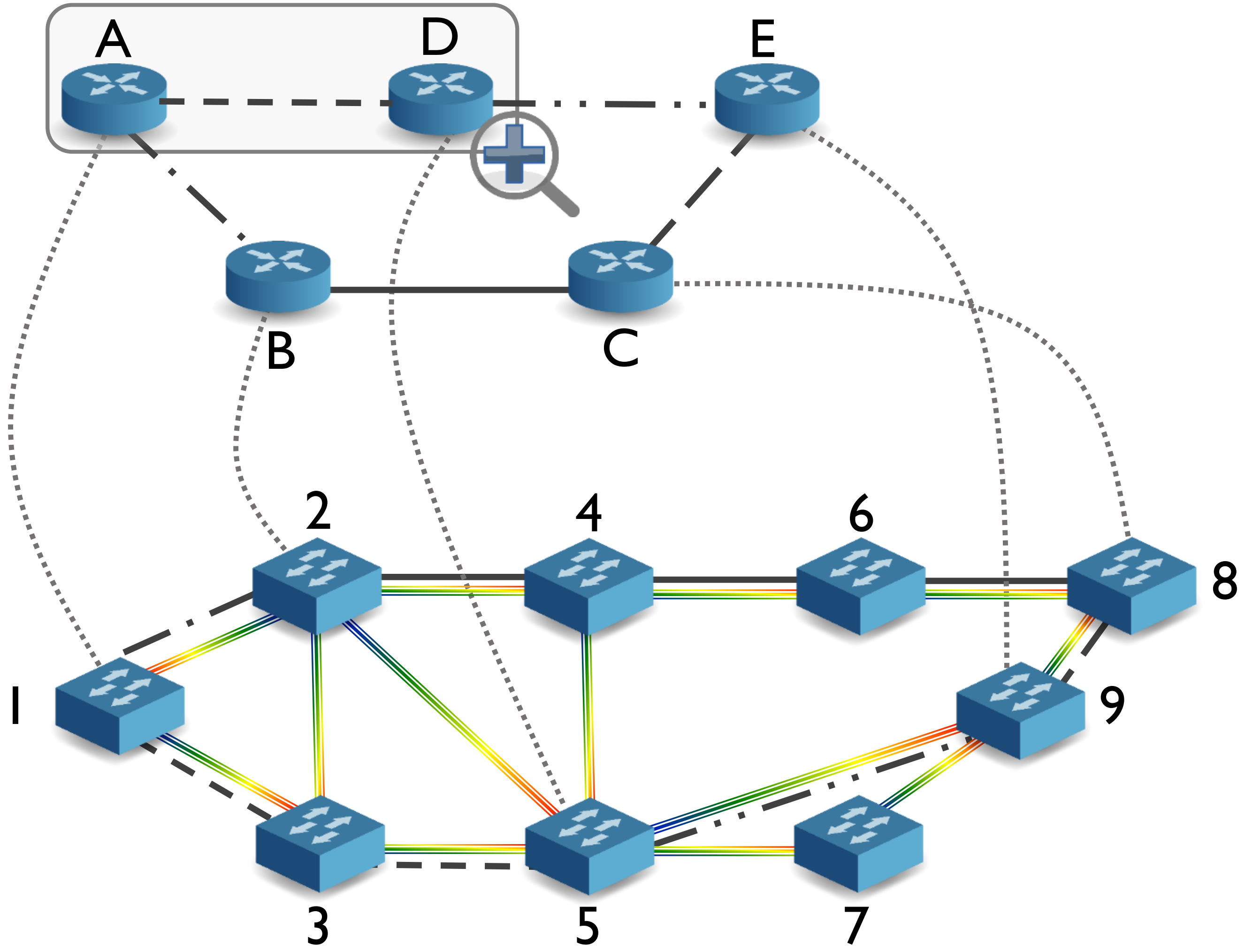
Performance of µNF-based VNF Chain

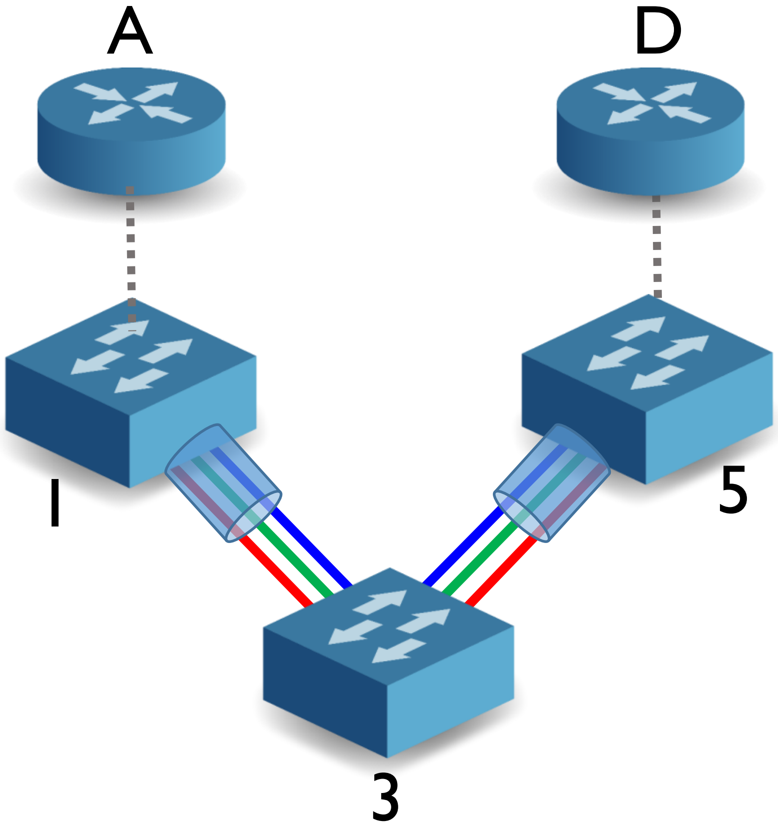
Edge Fw. →Monitoring → App. Fw:



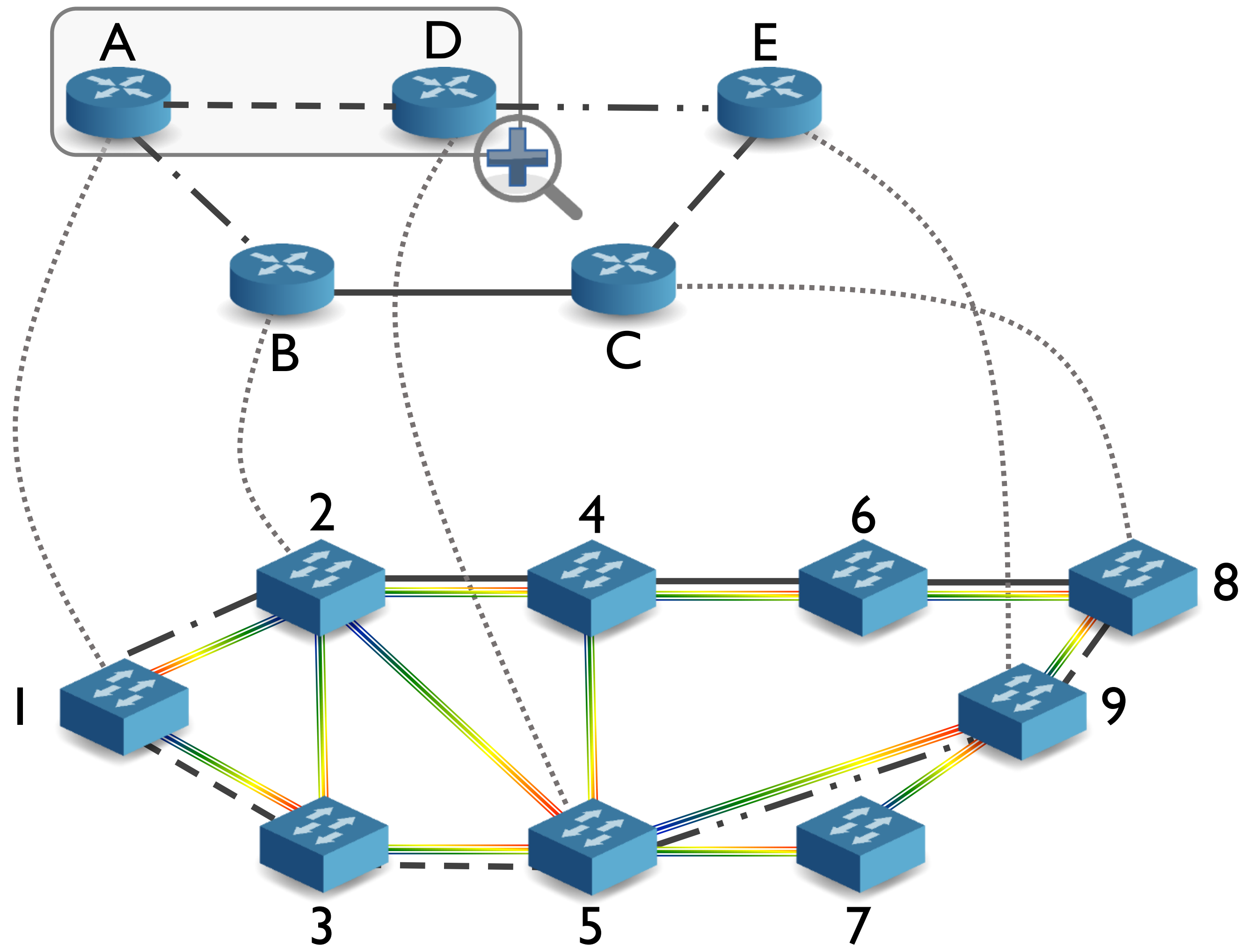
Click Element	CPU Cycles/packet saved in config-ii	Element weight in config-i
CheckIPHeader	27.8%	0.44%
HTTPClassifier	28.9%	47.8%
Overall	16.8%	-

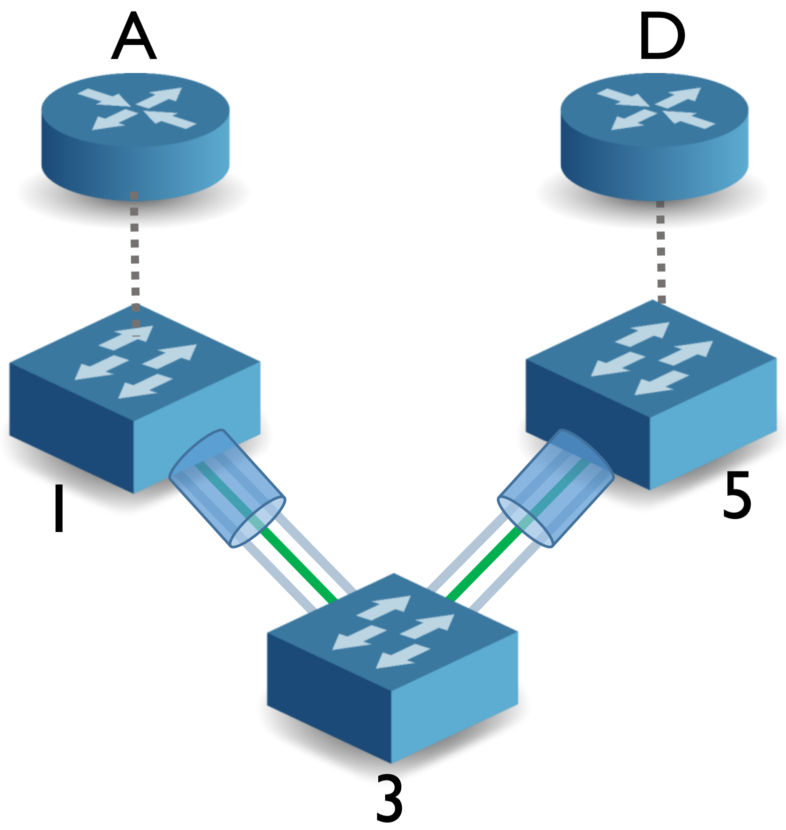
Multi-Layer IP-over-DWDM Network





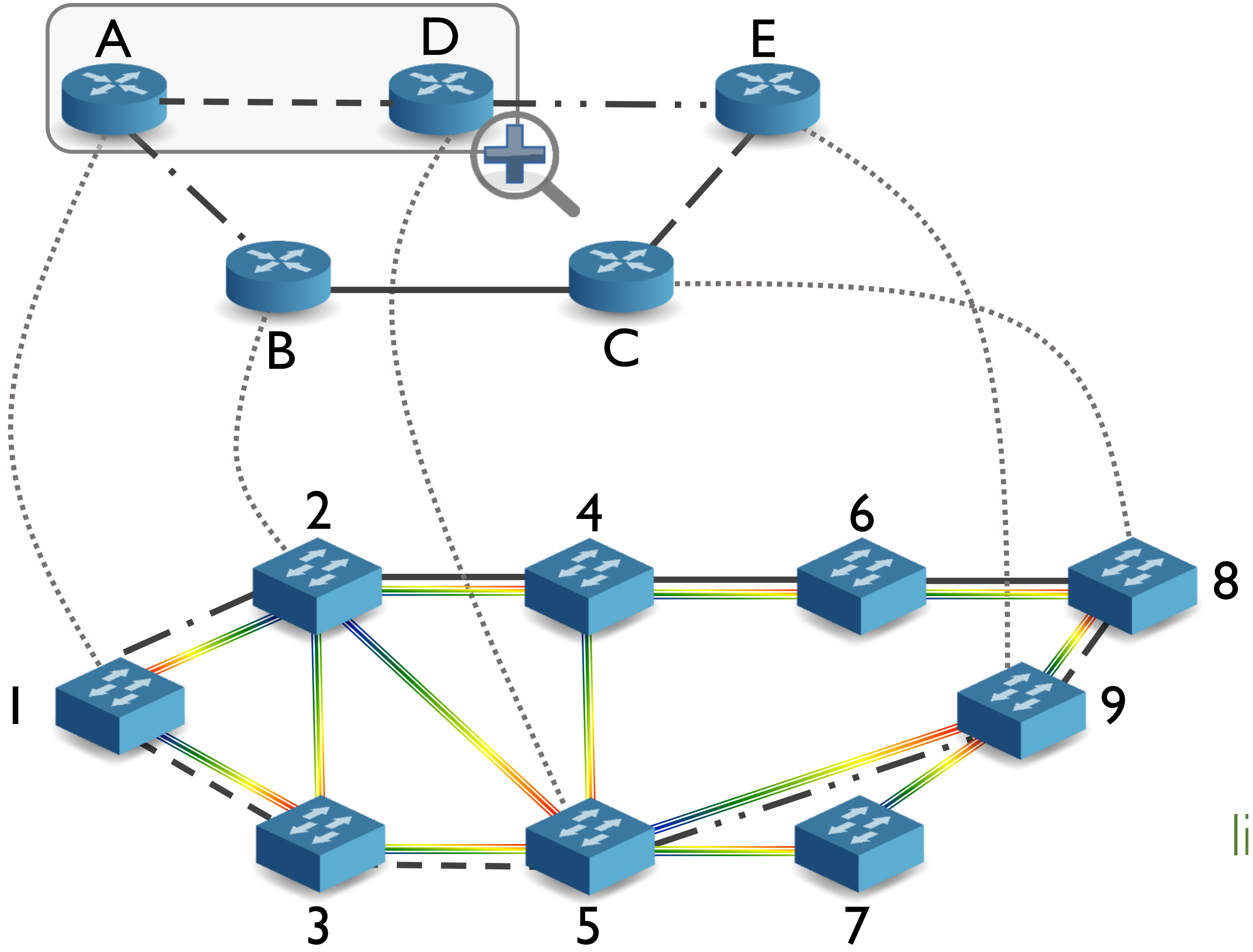
Multi-Layer IP-over-DWDM Network

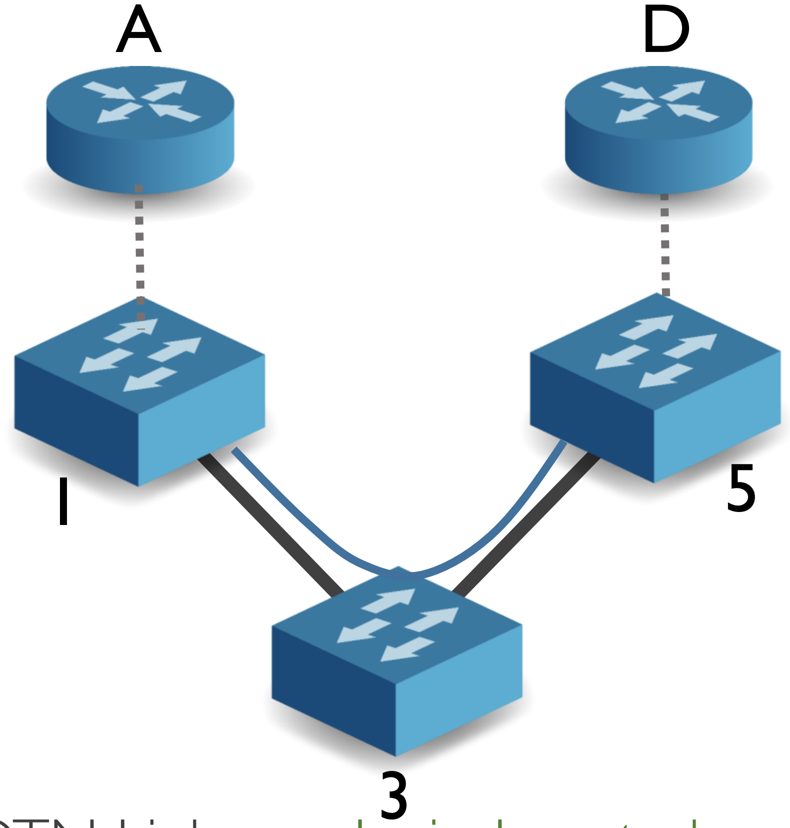




IP Links are tunneled over a single wavelength light-path

Multi-Layer IP-over-OTN Network





OTN Links are logical, routed over light-paths, and can multiplex multiple IP Links

Assumptions

1. Multi-Layer IP-over-OTN Network
2. OTN is static and OTN Links are already provisioned on light-paths in DWDM layer
3. No multi-path embedding; No node capacities

Comparison with State-of-the-art

D-VNE[1]	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

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

FAST-MULE: Challenges

Challenge - I

Joint Embedding on IP and Optical Layer

Solution

Collapse IP and Optical Layer into a single layer

Challenge - II

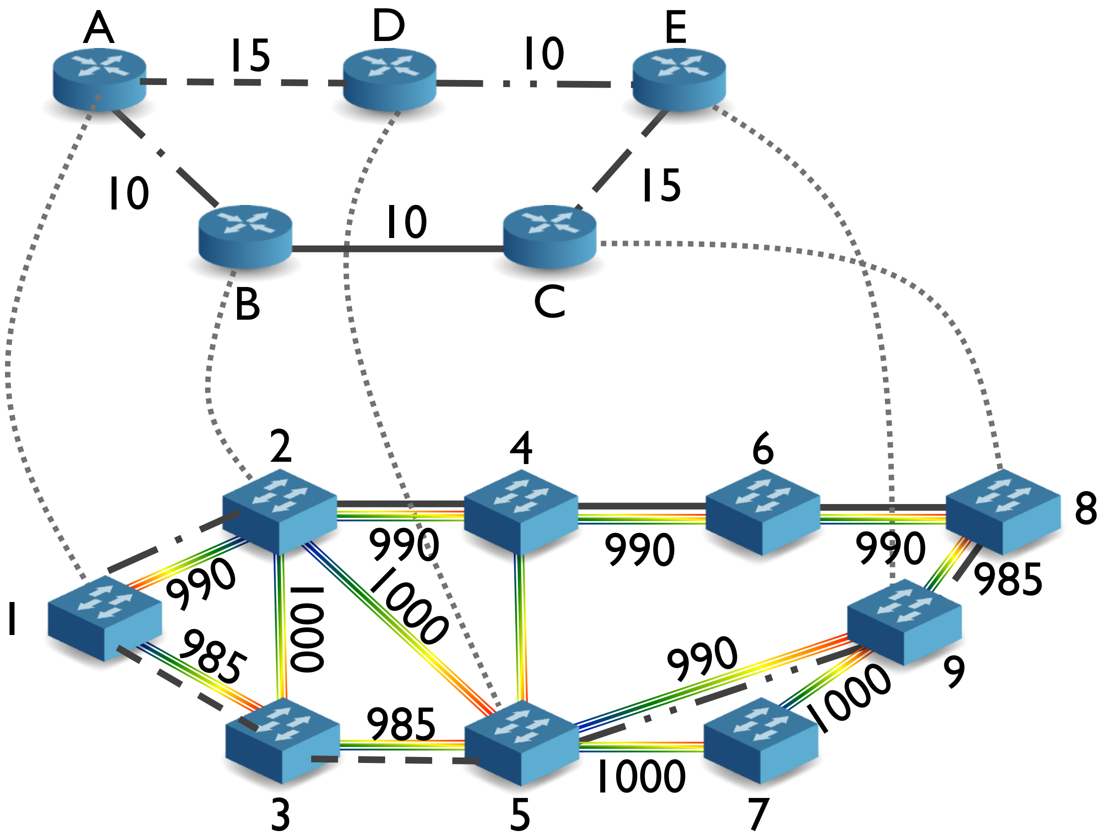
Joint embedding of virtual nodes and virtual links

Solution

Embed star subgraphs from VN in a single shot using min-cost max-flow

MULE: Example

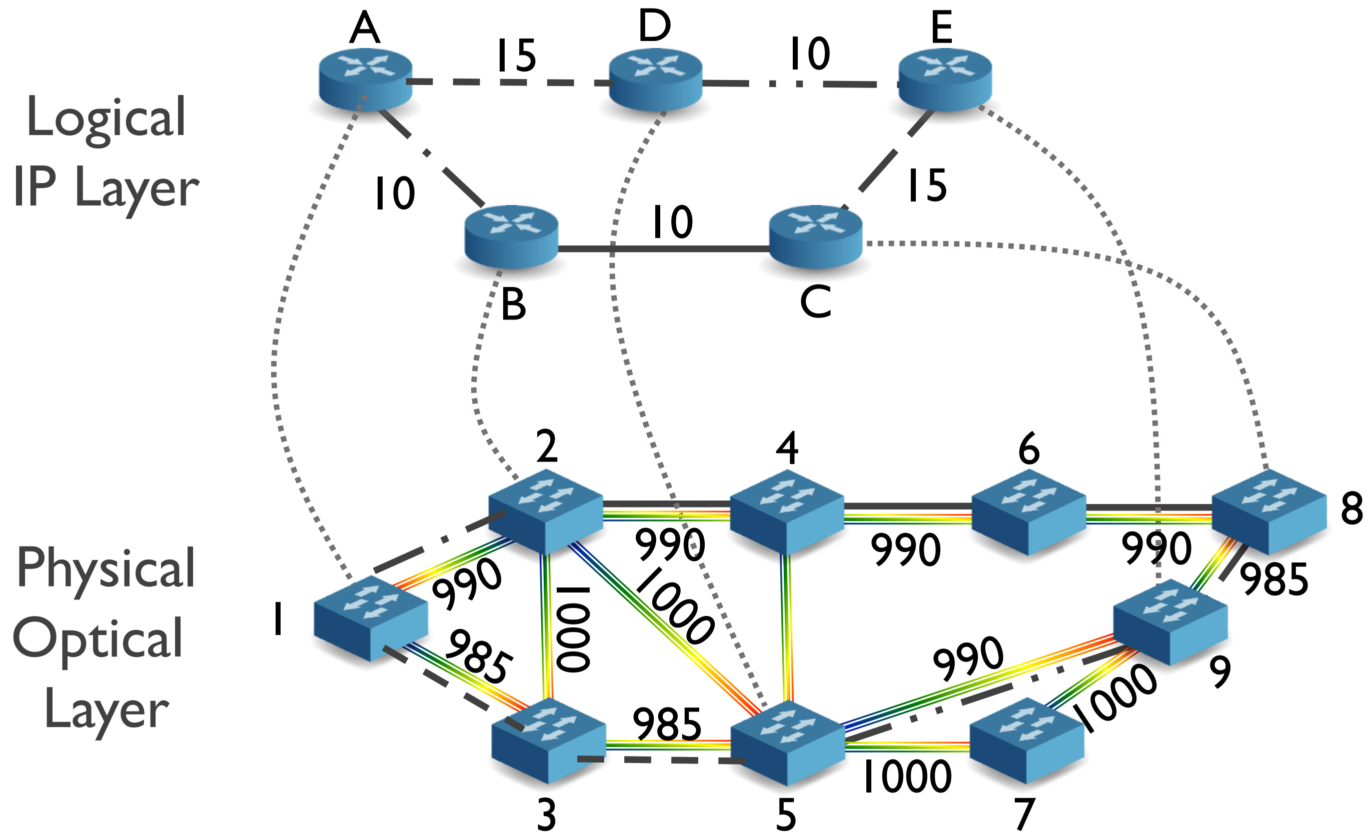
Given



Multi-Layer Substrate Network

MULE: Example

Given



Multi-Layer Substrate Network

MULE: Example

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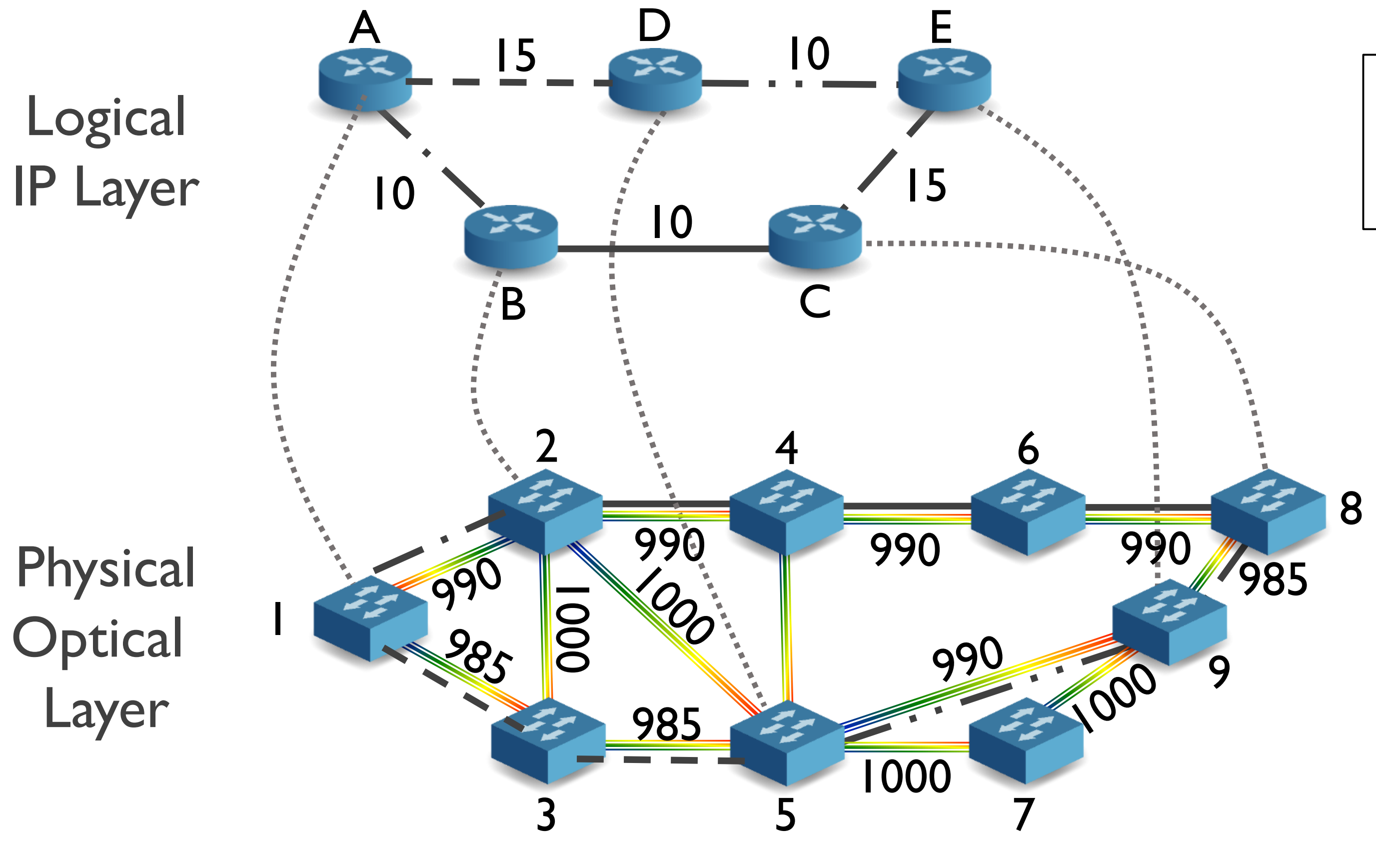
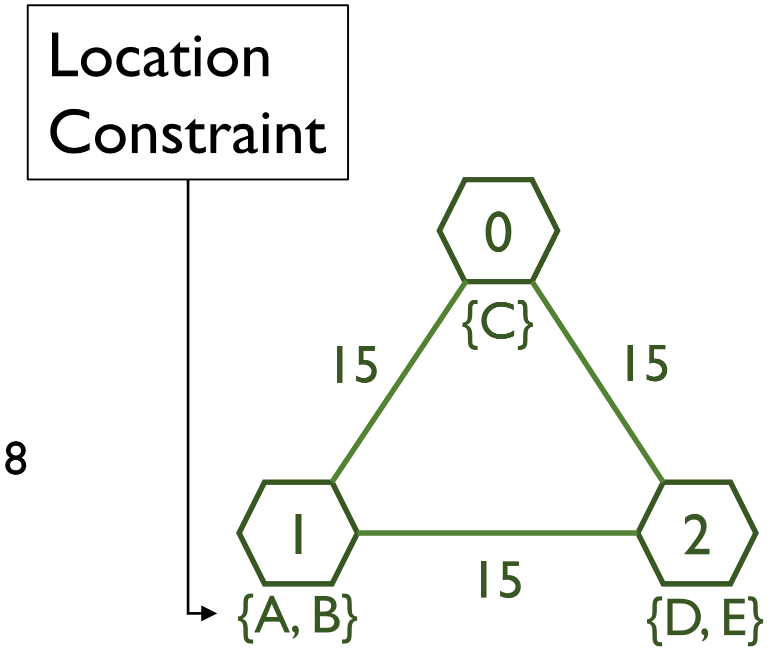


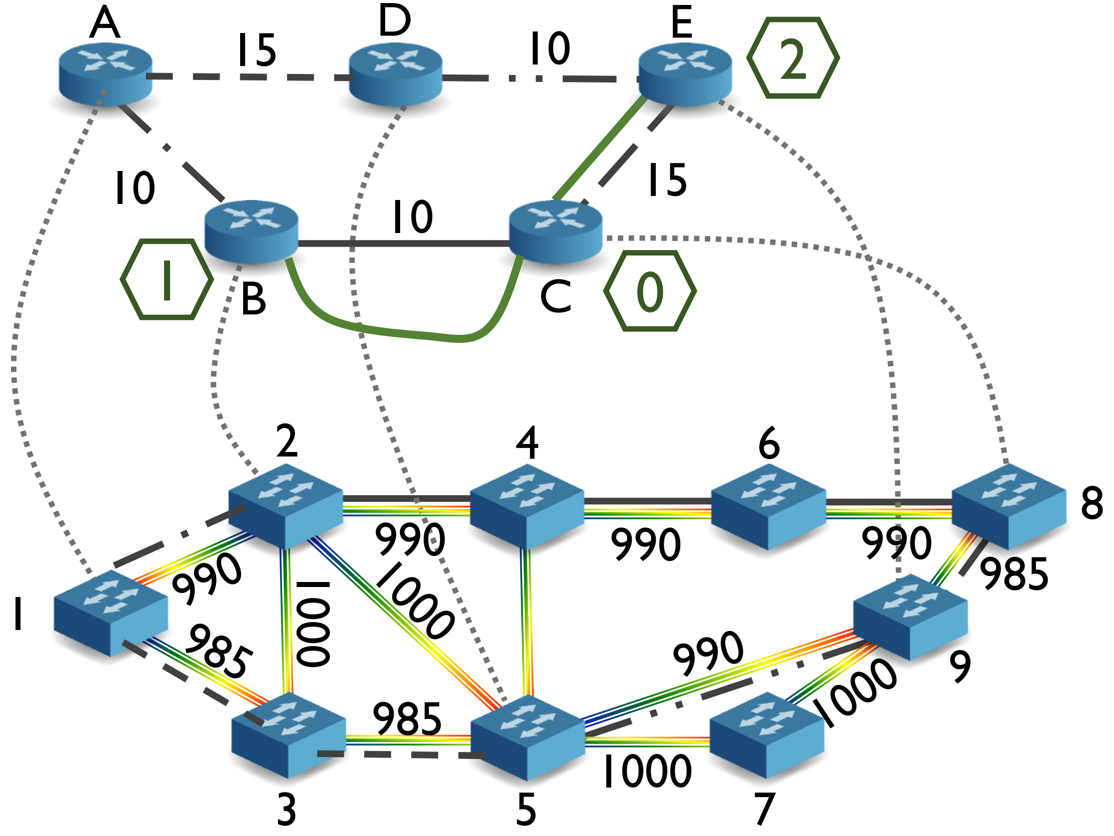
Multi-Layer Substrate Network



Virtual Network (VN)

MULE: Example

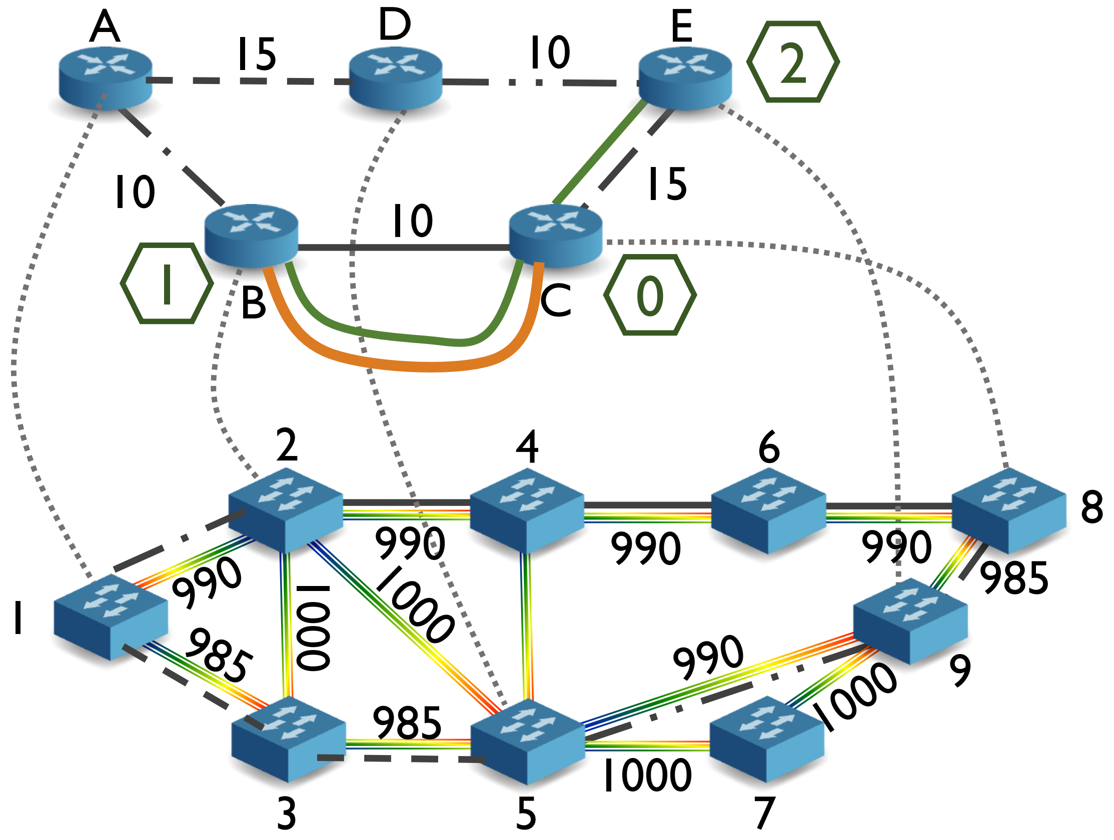
Embed the VN on the IP Layer



MULE: Example

Embed the VN on the IP Layer

Create new IP links (if necessary)

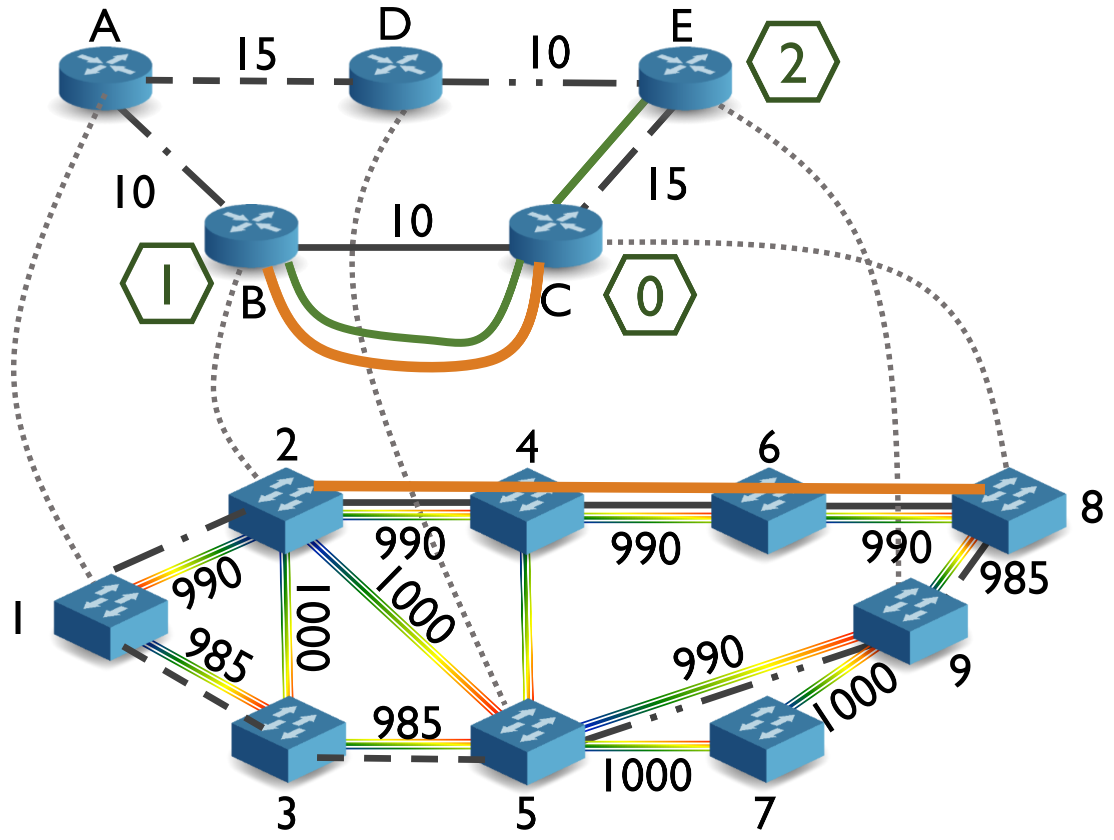


MULE: Example

Embed the VN on the IP Layer

Create new IP links (if necessary)

Embed the new IP links on Optical Layer

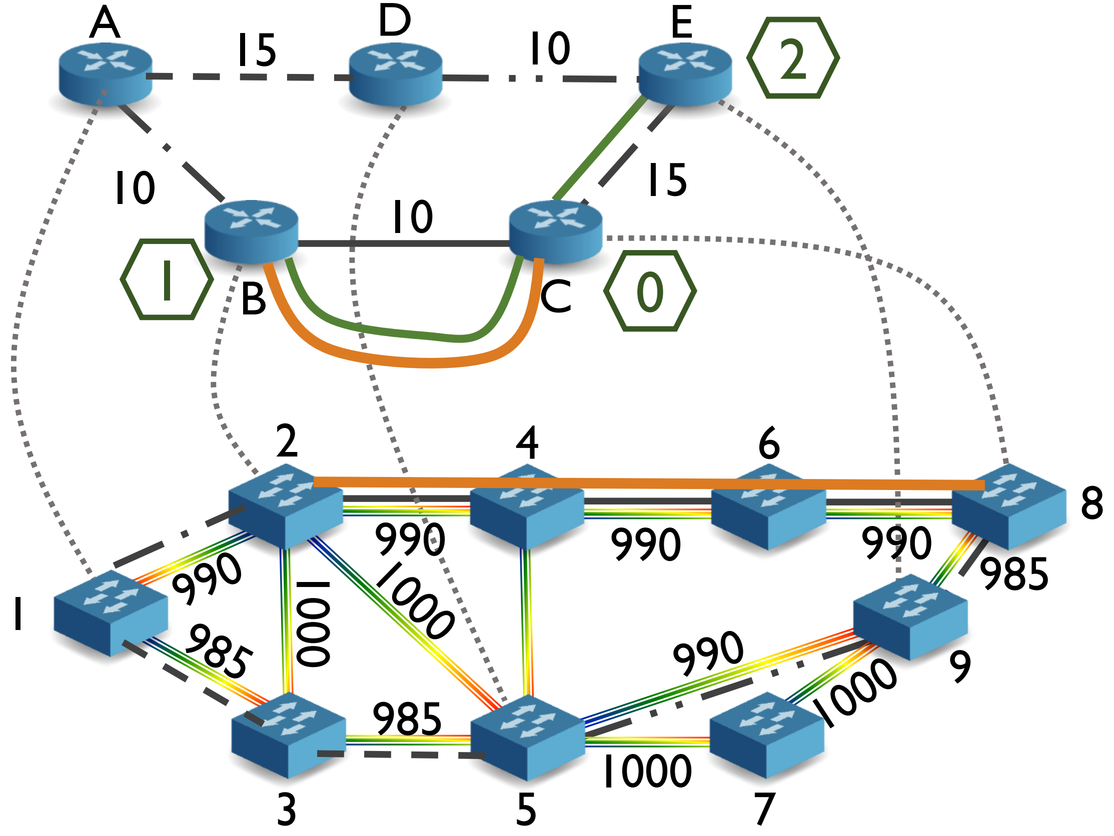


MULE: Example

Embed the VN on the IP Layer

Create new IP links (if necessary)

Embed the new IP links on Optical Layer



Objective: Jointly minimize resource allocation cost across both layers

State-of-the-art

Virtual Network Embedding

Extensive literature, mostly on single-layer VNE

Multi-layer Network Optimization

Mainly focused on multi-layer capacity planning; Node mapping is assumed to be known

Multi-layer Virtual Network Embedding

D-VNE[1]: Sequentially embeds virtual nodes and links on IP-over-DWDM network

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

FAST-MULE Performance Highlights

67% less resource consumption than D-VNE on avg.

Within ~47% resource consumption of optimal on avg.

2-3 Orders of magnitude faster than OPT-MULE

Research trends in SDN monitoring

Early 2010 — Accuracy-overhead trade-off in SDN monitoring

Mid 2010 — Sketch-based network monitoring

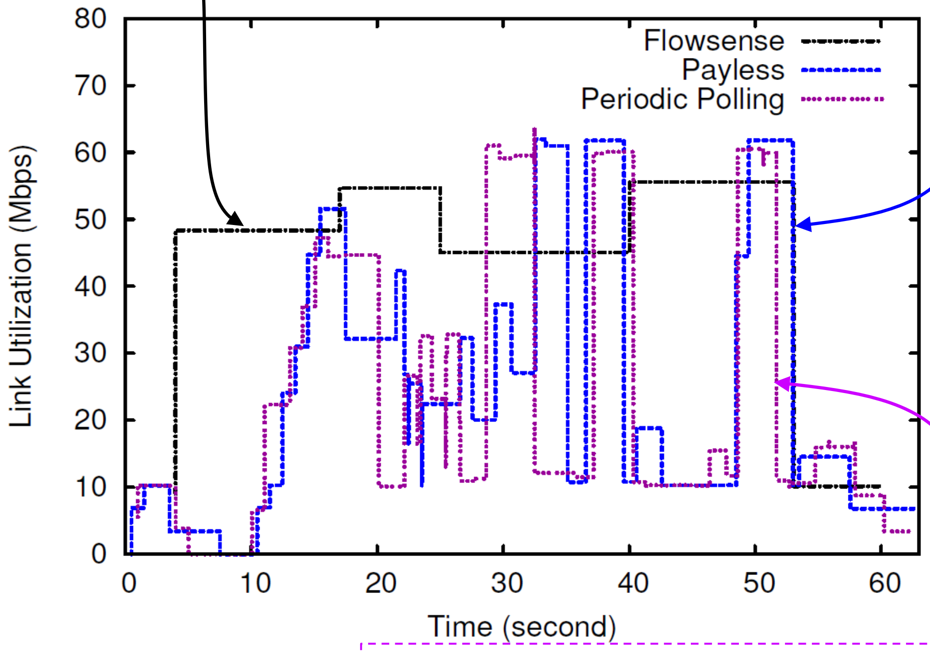
Mid 2010 to present — Exploit the capabilities of p4 compatible programmable switches for network monitoring.

Progress: Adaptive Flow Monitoring

- **PayLess: traffic intensity-aware adaptive monitoring algorithm**
  - Assign monitoring time out to flows
  - If no significant traffic change ($\leq\alpha$), increase the timeout (up to T_{max})
  - If change in traffic is significant ($\geq\beta$), decrease the timeout (up to T_{min})

FlowSense[1]: Misses the spikes; Far from original; overhead = 0.

PayLess: Closer to original; ~2x less overhead than periodic polling



Periodic-polling: Closest to original;

[1]C. Yu, *et al.* FlowSense: Monitoring Network Utilization with Zero Measurement Cost. PAM 2013.