Advanced Disaster-Resiliency Strategies for Next-Generation Metro Optical Networks in the Context of Smart Cities

Ph.D. Qualifying Exam

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Wednesday, September 18, 2019 10 a.m.

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ACK: NSF-JUNO2 CNS-1818972

Outline

1. Chapter 1: Background
2. Chapter 2: Logical network mapping with content connectivity against multiple link failures in metro optical networks
3. Chapter 3: Ongoing and future research

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Chapter 1: Background

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Urbanization

Population trend:

- World urban population: **55%** in 2018, **68%** in 2050 (expected)
- In U.S., urban population: **82%** in 2018 (Source: United Nations)

Pollutions:

Source: medicaldaily.com

Energy crisis:

Source: Indianfolk.com

Issues:

- Uncontrolled growth of urban population
- Limited natural and man-made resources

Solution: Smart cities

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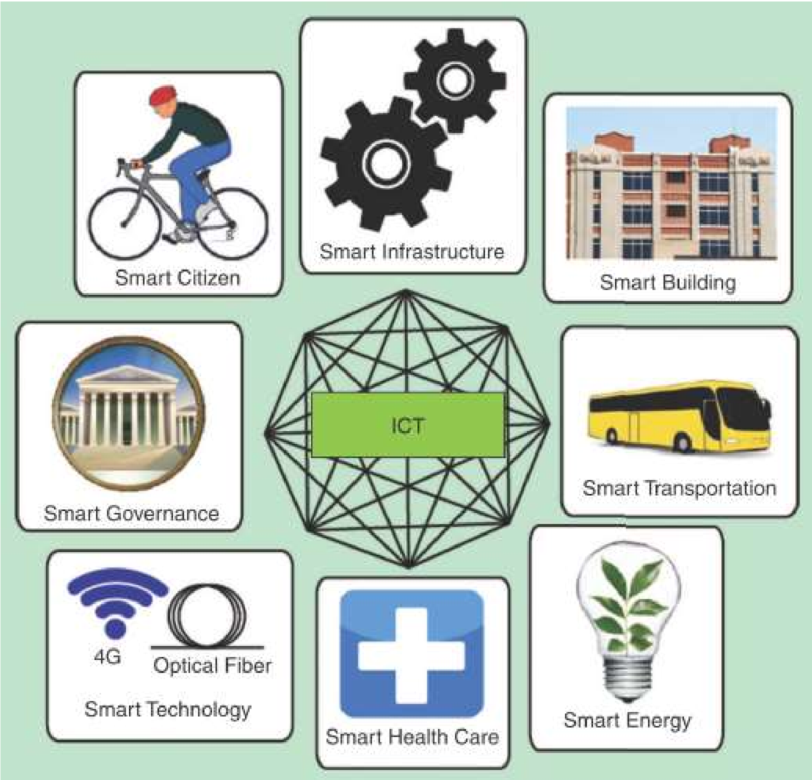
Smart Cities: Definition and Components

- **Smart cities**: effective approach to manage limited resources to serve largest possible population in order to improve:
  - ✓Livability,
  - ✓Workability,
  - ✓and Sustainability [1]



Smart city components [1]

[1] S. P. Mohanty, U. Choppali, and E. Kougianos, "Everything you wanted to know about smart cities: The Internet of things is the backbone," *IEEE Consumer Electronics Magazine*, vol. 5, no. 3, pp. 60-70, July 2016.

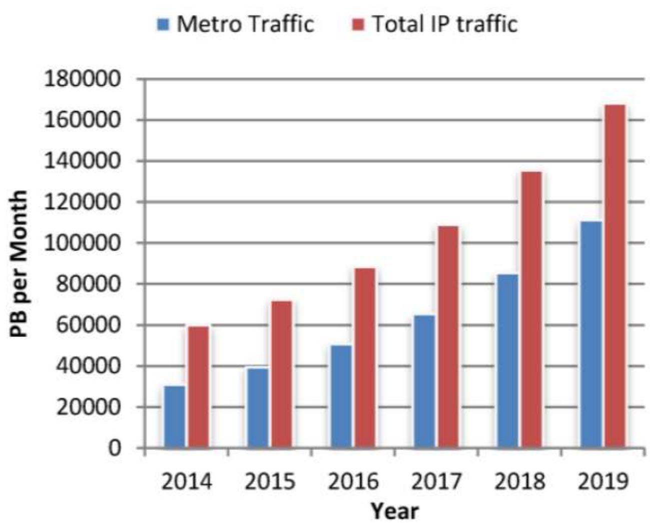
Smart Cities: Design Challenges

Reliable communication as one of design challenges [1], [2]

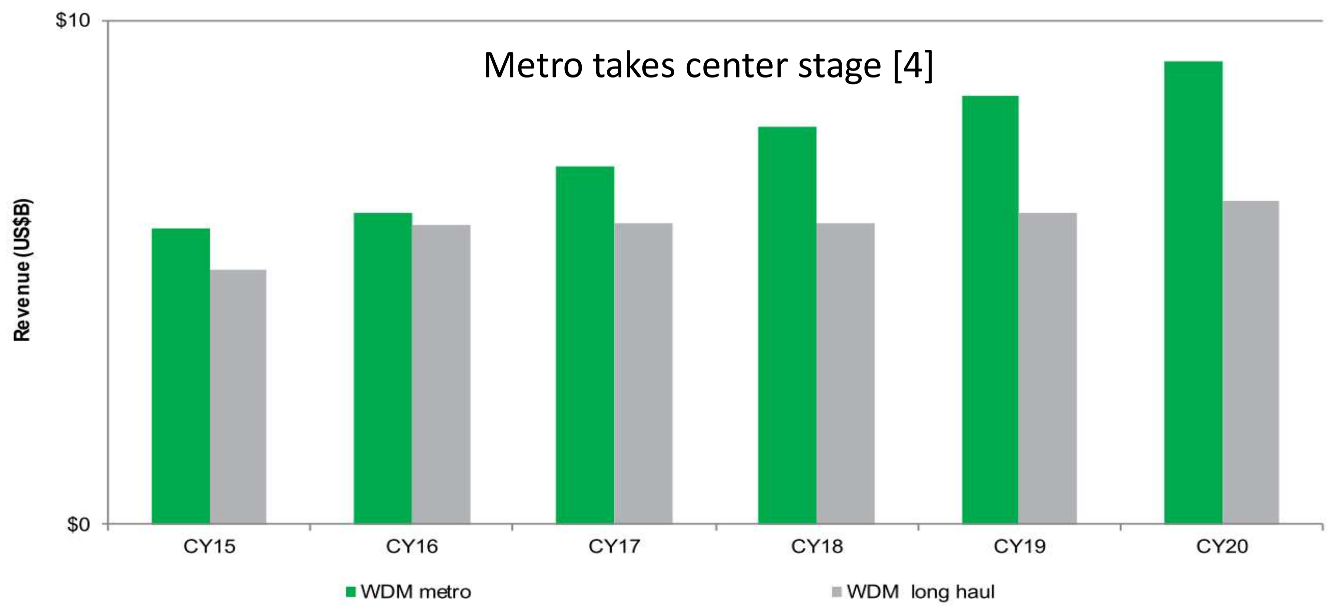
[1] S. P. Mohanty, U. Choppali, and E. Kougianos, "Everything you wanted to know about smart cities: The Internet of things is the backbone," *IEEE Consumer Electronics Magazine*, vol. 5, no. 3, pp. 60-70, July 2016.

[2] S. A. Shah, D. Z. Seker, M. M. Rathore, S. Hameed, S. Ben Yahia, and D. Draheim, "Towards Disaster Resilient Smart Cities: Can Internet of Things and Big Data Analytics Be the Game Changers?," *IEEE Access*, vol. 7, pp. 91885-91903, 2019.

Increasing Role of Metro Optical Networks



Metro traffic growth [3]



CY: Calendar Year

- 66% total IP traffic in 2019 [3]
- Metro hardware revenue surpasses long haul's [4]

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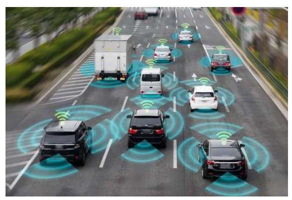
[3] Cisco, "Cisco Visual Networking Index: Forecast and Methodology, 2014–2019," *White Paper*, 2015.
[4] IHS Markit, "Trends in metro optical networks," *Report Excerpts*, 2018.

Emerging Services



New services

More stringent requirements for:

- ✓ Bandwidth
- ✓ Latency
- ✓ Reliability: For example, uRLLC in 5G requires 99.999% (five nines) availability [5]

Reliability in metro optical networks is gaining importance, particularly in the context of smart cities

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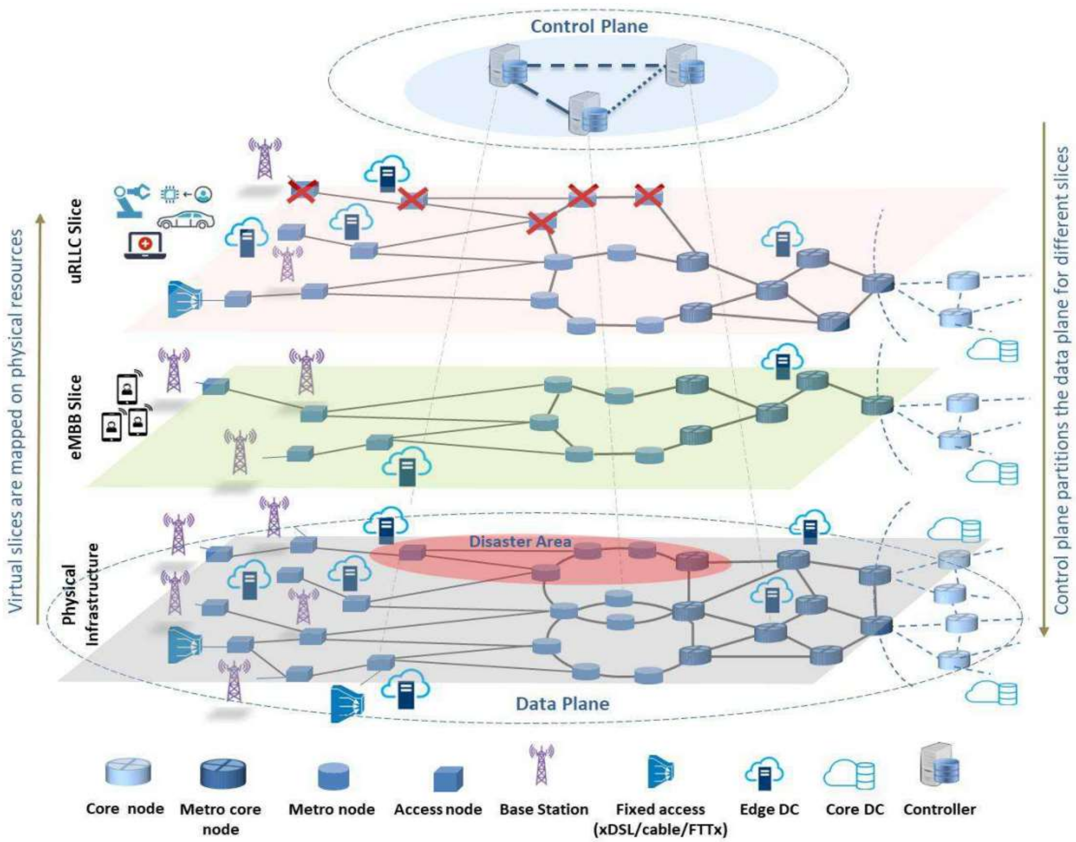
[5] S. Parkvall, E. Dahlman, A. Furuskar, and M. Frenne, "NR: The New 5G Radio Access Technology," *IEEE Communications Standards Magazine*, vol. 1, no. 4, pp. 24-30, Dec. 2017.

Reliability in Next-Generation Metro Optical Networks



Next-Generation Metro Optical Network Architecture [6]

Technology enablers:

- ✓ Software-Defined Networking
- ✓ Network Functions Virtualization
- ✓ Network Slicing

Disasters may disrupt services

Resiliency strategies must be adapted to the new architecture and enablers

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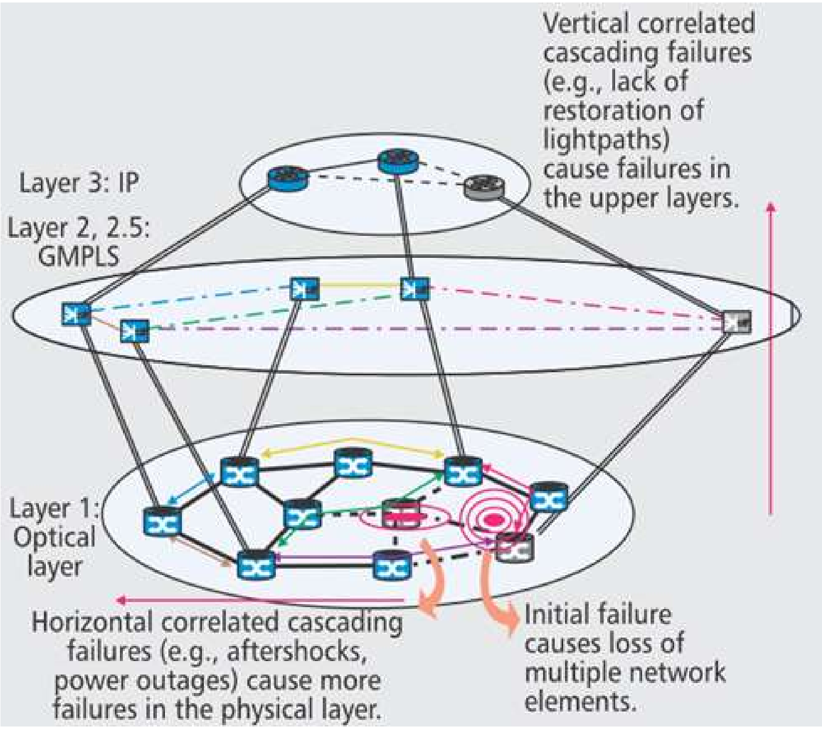
[6] S. Ferdousi, M. Tornatore, S. Xu, Y. Awaji, and B. Mukherjee, "Slice-Aware Service Restoration with Recovery Trucks for Optical Metro-Access Networks," *Proceedings of Global Communications Conference (Globecom)*, Dec. 2019.

Disaster Failure Characteristics

- Disruption of multiple links and nodes
- Cascading:
  - ✓horizontal (optical layer)
  - ✓vertical (higher layers)
- We focus on link failures (higher probability [8])



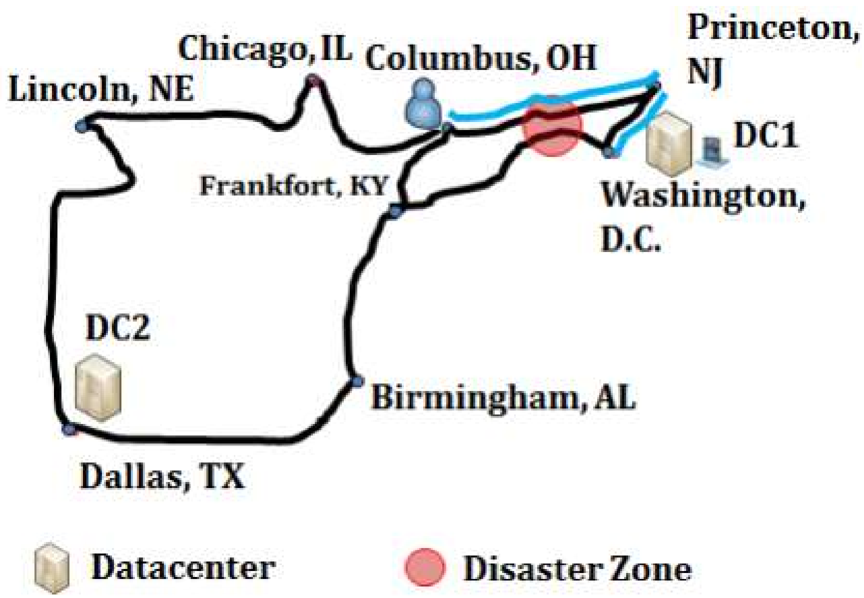
Cascading failures in optical networks [7]

[7] B. Mukherjee, M. F. Habib, and F. Dikbiyik, “Network adaptability from disaster disruptions and cascading failures,” *IEEE Communications Magazine*, vol. 52, no. 5, pp. 230-238, May 2014.

[8] P. Gill, N. Jain, and N. Nagappan, “Understanding network failures in data centers: measurement, analysis, and implications,” *Proceedings of ACM SIGCOMM*, vol. 41, no. 4, Aug. 2011.

Network Connectivity (NC)

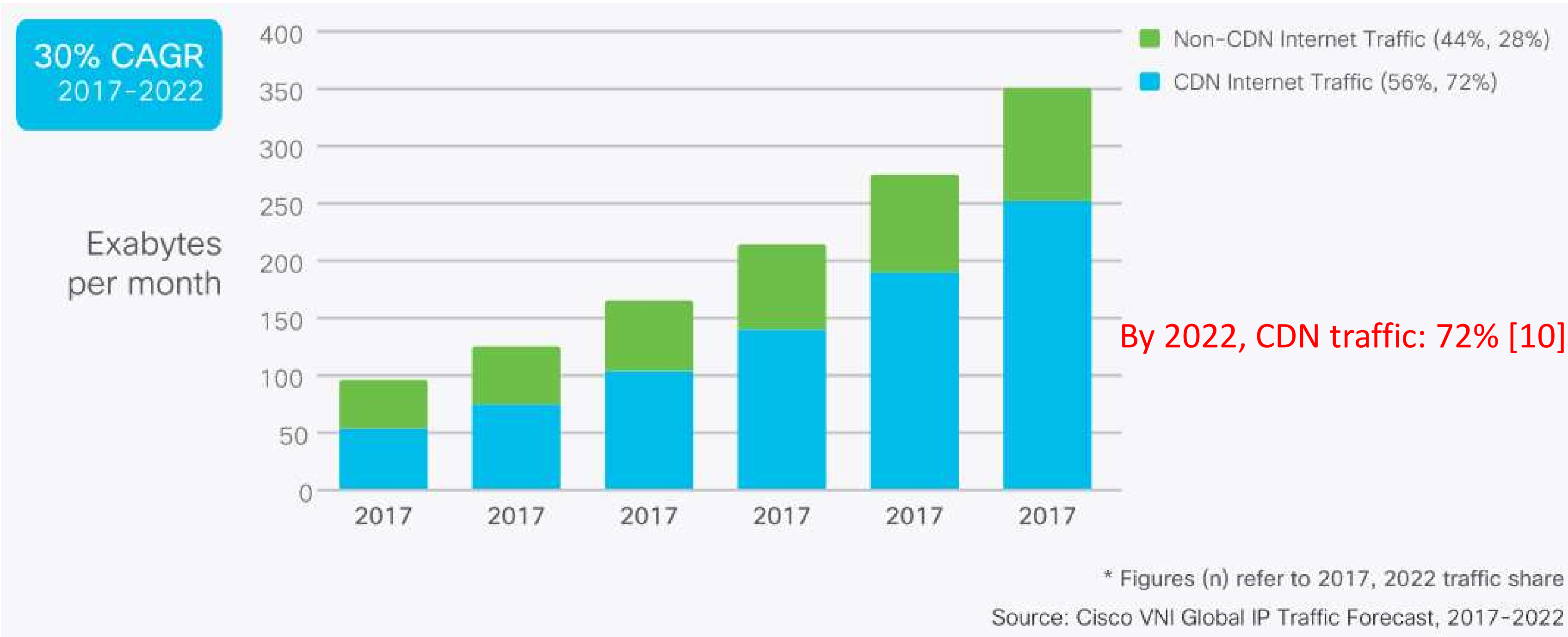
- Reachability of every network node from all other nodes
- Default metric for network survivability
- In case of disasters, NC may not be possible



Scenario where NC is not possible [9]

[9] M. F. Habib, M. Tornatore, and B. Mukherjee, "Fault-tolerant virtual network mapping to provide Content Connectivity in optical networks," *Proceedings of Optical Fiber Communication Conference (OFC)*, Mar. 2013.

Increasing Role of Content Delivery Networks (CDN)



By 2022, CDN traffic: 72% [10]

Content connectivity -> Service continuity (most applications)

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[10] Cisco, "Cisco Visual Networking Index: Forecast and Trends 2017–2022," *White Paper*, Feb. 2019.

Content Connectivity

- ✓ Reachability of content from every node in a network under a given failure scenario [9]
- ✓ Important survivability metric
- ✓ Possible in some scenarios NC impossible

Content Connectivity is guaranteed after disaster [9]

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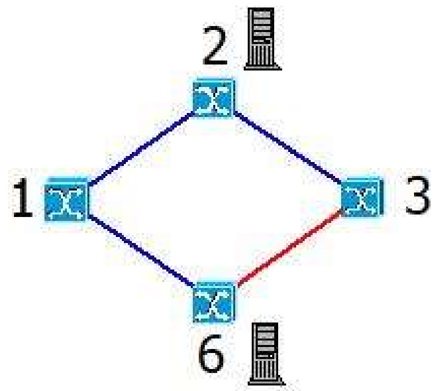
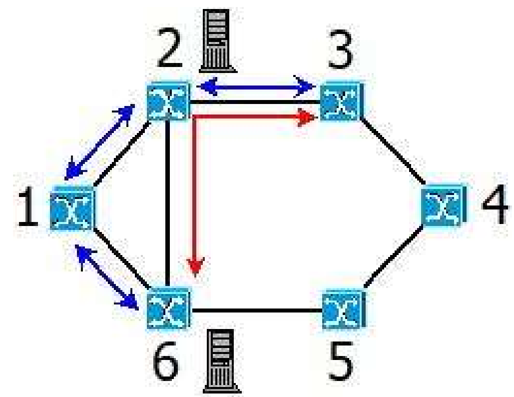
[9] M. F. Habib, M. Tornatore, and B. Mukherjee, "Fault-tolerant virtual network mapping to provide Content Connectivity in optical networks," *Proceedings of Optical Fiber Communication Conference (OFC)*, Mar. 2013.

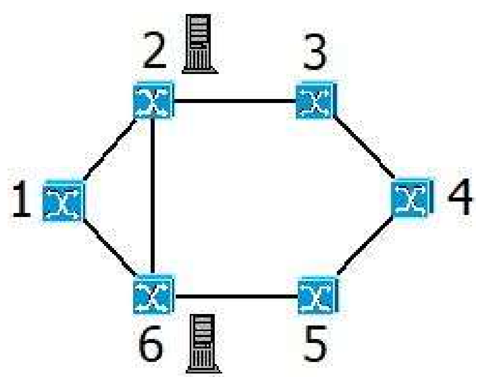
Mapping With Content Connectivity



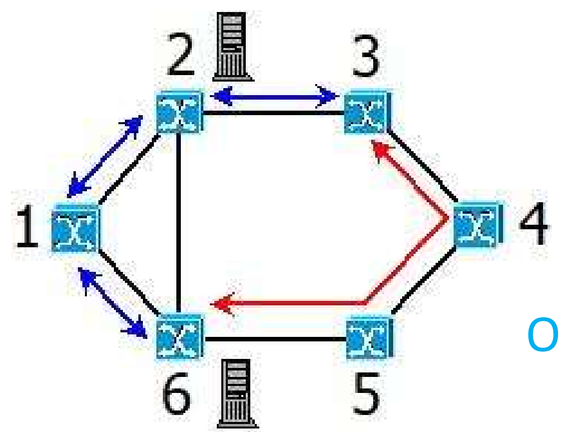
Logical topology



2-3 link failure disconnects 3 from content



Physical topology



Content-connected against single link failures

Optimization problem

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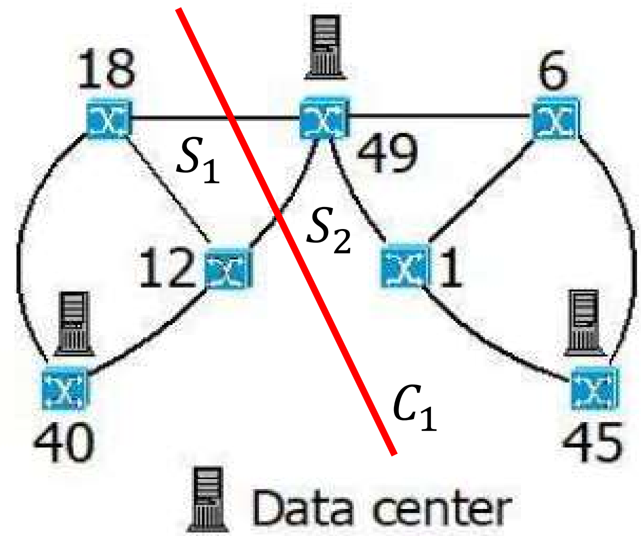
Chapter 2:
Logical Network Mapping With Content Connectivity Against Multiple Link Failures in Metro Optical Networks

(Preliminary results in this chapter have been submitted to ANTS 2019)

Cut and Cutset of a Network

- *Cut*: partition of the network into two disconnected segments (e.g., two node groups S_1 and S_2)
- *Cutset*: set of links with one endpoint in S_1 and the other in S_2



Logical topology

- ✓ C_1 is a cut
- ✓ $S_1 = \{12, 18, 40\}$
- ✓ $S_2 = \{1, 6, 45, 49\}$
- ✓ {18-49, 12-49} is a cutset

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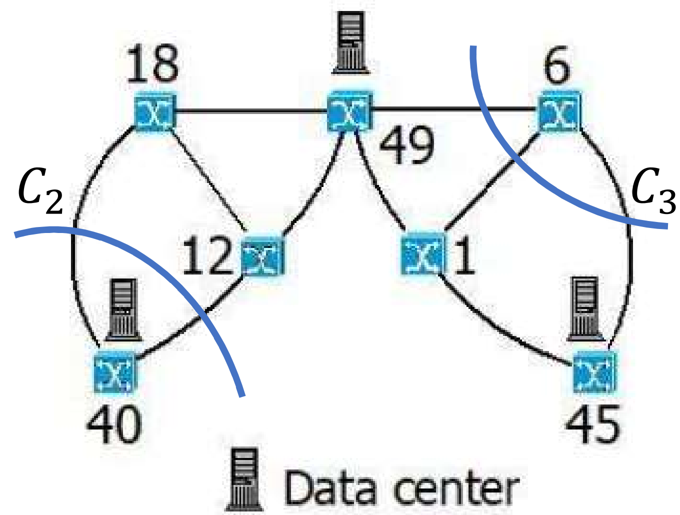
Network Cutset and Content Cutset

- Network Connectivity (NC) cutset:
  - ✓C_2
  - ✓Removal all links in C_2 violates NC
- Content Connectivity (CC) cutset:
  - ✓C_3
  - ✓Removal all links in C_3 disconnects node 6 from content
  - ✓Nodes co-located with datacenters are content-connected



Logical topology

Content available at all DCs

Problem Statement

Given:

- ✓Logical topology
- ✓Physical topology

Objective:

- ✓Minimize network resource usage

Output:

- ✓Mapping with content connectivity after n link failures

Problem Notations

- $\mathrm{NC}-n$: Network Connectivity (NC) after failures on n physical links
- $\mathrm{CC}-n$: Content Connectivity (NC) after failures on n physical links

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Input Parameters

- $G_P(V_P, E_P)$: physical topology (graph)
- V_P: set of physical nodes
- E_P: set of physical links
- $G_L(V_L, E_L)$: logical topology (graph)
- V_L: set of logical nodes
- E_L: set of logical links
- D: set of Datacenter, $D \subset V_L$
- F_{ij}: number of fiber from i to j
- W: number of wavelength/fiber
- n: number of physical link failures
- P_n: set of n physical links
- C_{cc}: set of content-connected cutsets (next slides)

P_n: Set of n Physical Links

- Number of physical nodes: $N_P = |V_P|$, where $|.|$ set cardinality
- Number of physical links: $L_P = |E_P|$
- Select n links out of L_P links: Combination without order and repetition
- Total number of valid sets:

$$\frac{L_P!}{n!\,(L_P - n)!}$$

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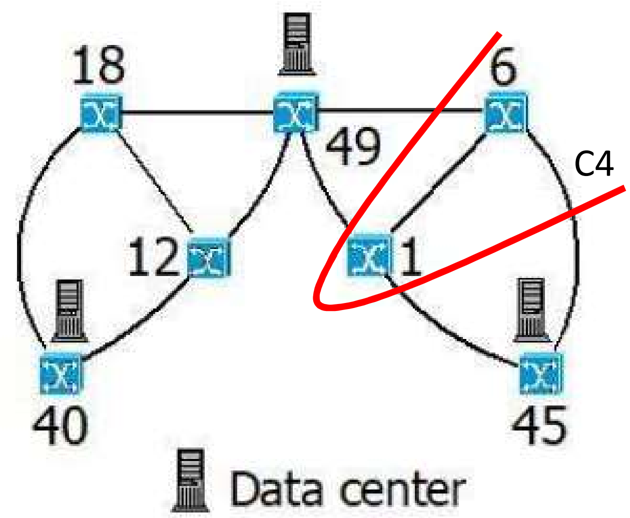
C_{CC}: Set of Content-Connected Cutsets

- Number of logical nodes: $N_L = |V_L|$
- Number of logical links: $L_L = |E_L|$
- Content-Connected (CC) cutset:
  - ✓ C4 (for example)
  - ✓ $S_1 = \{1, 6\}$
  - ✓ $S_2 = V_L - S_1 = \{12, 18, 40, 45, 49\}$
  - ✓ $S_1 \cap D = \{40, 45, 49\} = \emptyset$
- C_{CC}: enumeration of all CC cutsets



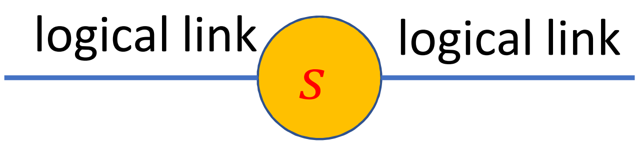
Logical topology

For example, this logical topology has 30 CC cutsets

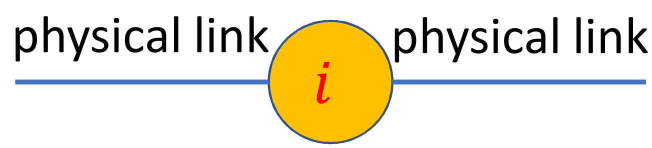
CC-n Existence

Theorem 1: Given $G_P(V_P, E_P)$, $G_L(V_L, E_L)$, and D, to find the mapping of G_L over G_P that guarantees CC-n, the following conditions must be satisfied:

- ✓ each logical node $s \in V_L - D$ has a nodal degree $\delta(s) \geq n + 1$, and
- ✓ each physical node $i \in V_P : i = s$ has a nodal degree $\delta(i) \geq n + 1$.



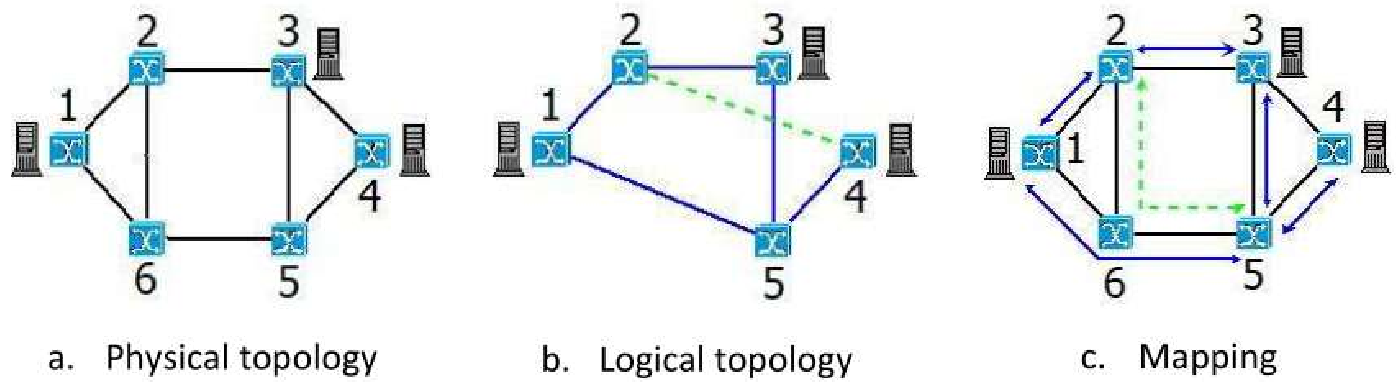
$\delta(s) = 2$, no CC-2 solution for node s



$\delta(i) = 2$, no CC-2 solution mapped over node i

Problem Variable

- Variable definition (binary):
  - ✓ $f_{ij}^{st} = 1$ if logical link st is mapped over physical link ij
  - ✓ $f_{ij}^{st} = 0$ otherwise



For example: $f_{16}^{15} = f_{65}^{15} = 1,\ f_{ij}^{15} = 0, \forall \text{ij} \notin \{16,65\}$

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CC-n Enforcement

Theorem 2: Given $G_P(V_P, E_P)$, $G_L(V_L, E_L)$, D, let $P_n = \{\{P_n^k\}: |\{P_n^k\}| = n, \{P_n^k\} \in E_P\}$ be set of all possible combinations of n distinct physical links, and $C_{CC} = \{C_{CC}^l(S_l, V_L - S_l): S_l \cap D = \emptyset\}$ be set of logical topology content-connected cutsets where the removal of all logical links in each cutset C_{CC}^l disconnects G_L and divides V_L into two disjoint sets with one set without datacenters, the mapping of G_L over G_P is CC-n if and only if:

$$\sum_{ij \in P_n^k, st \in C_{CC}^l} f_{ij}^{st} \leq |C_{CC}^l| - 1, \forall P_n^k \in P_n, \forall C_{CC}^l \in C_{CC}.$$

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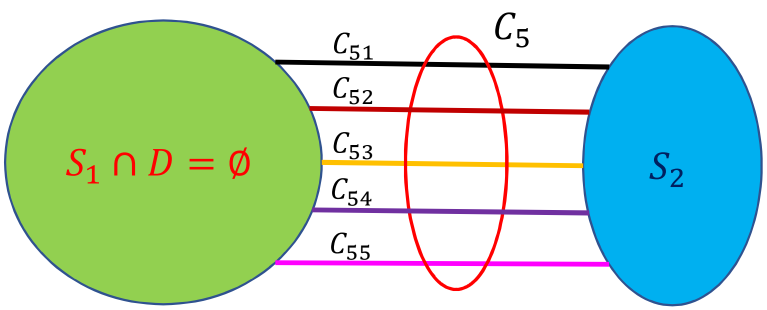
CC-n Enforcement

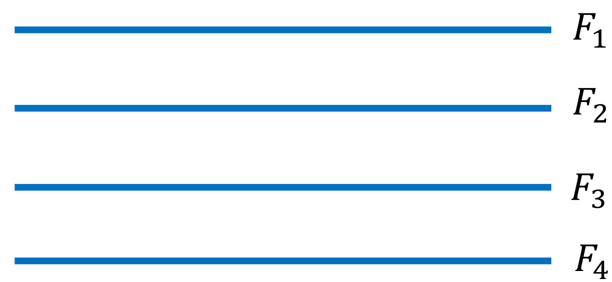
Theorem 2: Example $n = 3$ (survivable against 3 link failures)



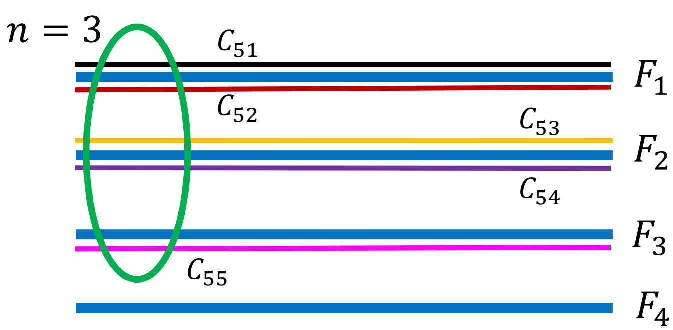
Content-Connected Cutset C_5

mapping

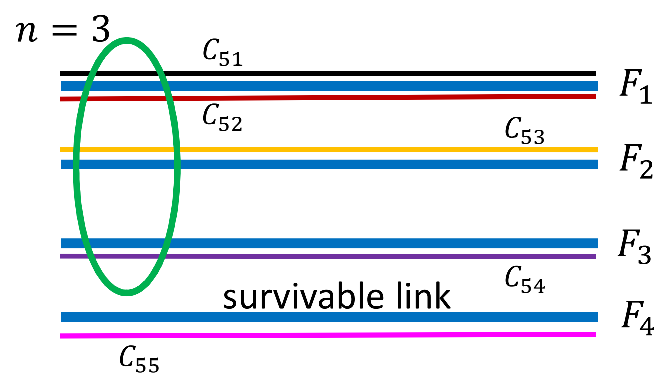
Target: CC-3 ($n = 3$)



Physical links



CC-3 not survivable



CC-3 survivable

Repeat for all possibilities in networks

Mathematical Formulations of CC-n Problem

Objective function:

$$\min \sum_{ij \in E_P,\, st \in E_L} f_{ij}^{st}$$

- ✓ Result in an ILP
- ✓ Lower complexity

Subject to:

Capacity Constr.

- $\sum_{st \in E_L} f_{ij}^{st} \leq F_{ij} \times W, \forall ij \in E_P$

Flow Constr.

- $\sum_{j:ji \in E_P} f_{ji}^{st} - \sum_{j:ij \in E_P} f_{ij}^{st} = \begin{cases} -1 \text{ if } i = s \\ 1 \quad \text{if } i = t \\ 0 \text{ otherwise} \end{cases}$

  $\forall i \in V_P, \forall st \in E_L$

CC-n Constr.

- $\sum_{ij \in P_n^k, st \in C_{cc}^l} f_{ij}^{st} \leq \left| C_{cc}^l \right| - 1$

  $\forall P_n^k \in P_n, \forall C_{cc}^l \in C_{cc}$

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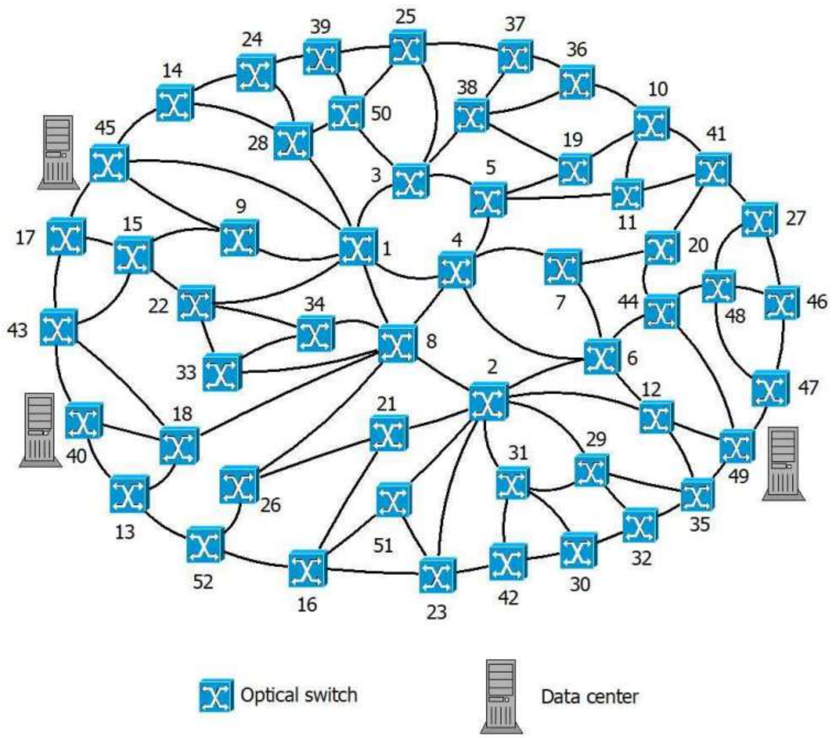
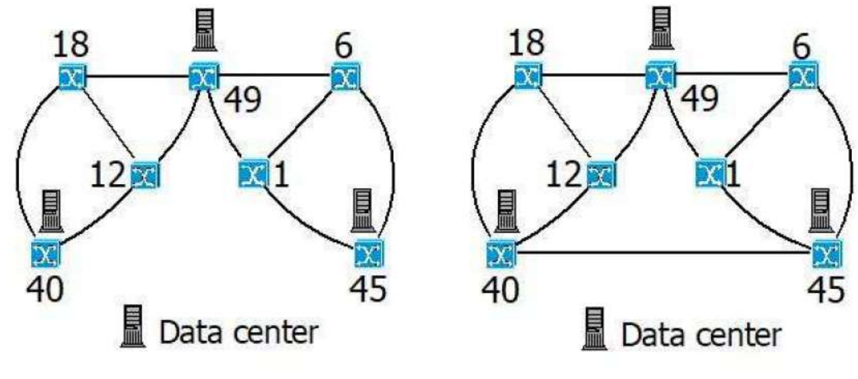
Illustrative Numerical Examples



Physical Network: Modified Telecom Italia Network

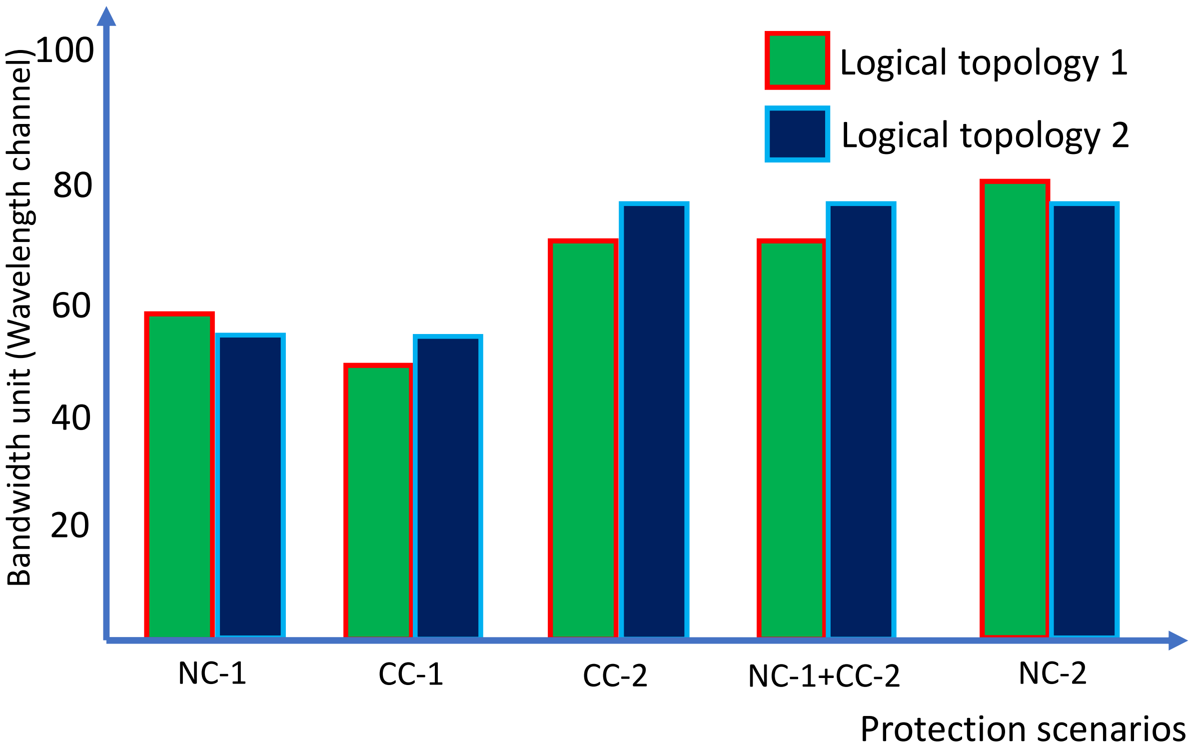


a) Logical topology 1 b) Logical topology 2

Logical topologies

- ✓ Physical network: 52 nodes, 98 bidirectional links
- ✓ Logical topologies: 7 nodes, 10 bidirectional links (a), and 11 bidirectional links (b)

Illustrative Numerical Examples



Ongoing: generalizing scenarios

- ✓ NC > CC
- ✓ NC = CC
- ✓ NC not possible but CC possible
- ✓ DC location impact

Our new approach is more generic (arbitrary n) and more scalable than those in [10], [11]

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[10] M. F. Habib, M. Tornatore, and B. Mukherjee, "Fault-tolerant virtual network mapping to provide Content Connectivity in optical networks," *Proceedings of OFC*, Mar. 2013.

[11] A. Hmaity, F. Musumeci, and M. Tornatore, "Survivable virtual network mapping to provide content connectivity against double-link failures," *Proceedings of DRCN*, Mar. 2016.

Number of Variables and Constraints

- Variable (only one): f_{ij}^{st}

variables: $L_P \times L_L = 196 \times 20 = 3920$

Capacity Constr.

- $\sum_{st \in E_L} f_{ij}^{st} \leq F_{ij} \times W, \forall ij \in E_P$

constr.: $L_P = 196$

Flow Constr.

- $\sum_{j:ji \in E_P} f_{ji}^{st} - \sum_{j:ij \in E_P} f_{ij}^{st} = \begin{cases} -1 \text{ if } i = s \\ 1 \quad \text{if } i = t \\ 0 \text{ otherwise} \end{cases}$

$\forall i \in V_P, \forall st \in E_L$

constr.: $N_P \times L_L = 52 \times 20 = 1040$

CC-n Constr.

- $\sum_{ij \in P_n^k, st \in C_{cc}^l} f_{ij}^{st} \leq \left| C_{cc}^l \right| - 1$

$\forall P_n^k \in P_n, \forall C_{cc}^l \in C_{cc}$

constr. ($n = 2$): $|P_n| \times |C_{cc}| = 19{,}110 \times 30 = 573{,}300$

Sum up

Totally, 3,920 variables, 574,536 constraints ($n = 2$)

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Note: Physical topology + Logical topology 1

Number of Variables and Constraints Comparison

Note: Physical topology + Logical topology 1

Scenarios	Previous works		This work	
	# Variables	# Constraints	# Variables	# Constraints
NC-1	3,920 [13]	25,932 [13]	3,920	25,932
CC-1	90,220 [11]	90,423 [11]	3,920	7,116
CC-2	8,116,420 [12]	64,297,083 [12]	3,920	574,536
NC-1+CC-2	8.116,420 [12]	64,297,083 [12]	3,920	599,232
NC-2	NA	NA	3,920	2,409,096

CC-1: # var and # constr. reduced by factor of 23 and 12

CC-2: # var and # constr. reduced by factor of 2×10^3 and 112

NC-2: Slowly increasing

Variables independent of n

[11] M. F. Habib, M. Tornatore, and B. Mukherjee, "Fault-tolerant virtual network mapping to provide Content Connectivity in optical networks," *Proceedings of OFC*, Mar. 2013.

[12] A. Hmaity, F. Musumeci, and M. Tornatore, "Survivable virtual network mapping to provide content connectivity against double-link failures," *Proceedings of DRCN*, Mar. 2016.

[13] E. Modiano and A. Narula-Tam, "Survivable lightpath routing: a new approach to the design of WDM-based networks," *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 4, pp. 800–809, May 2002.

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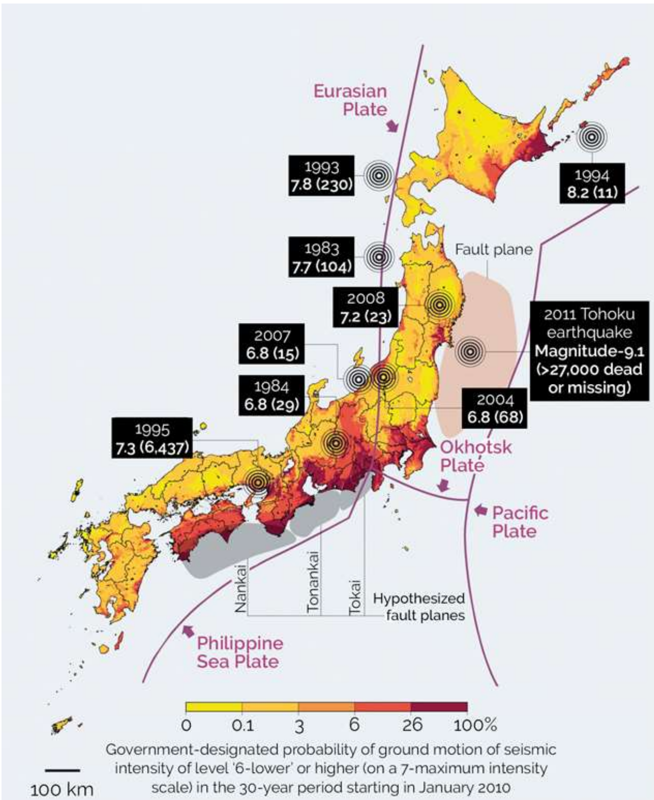
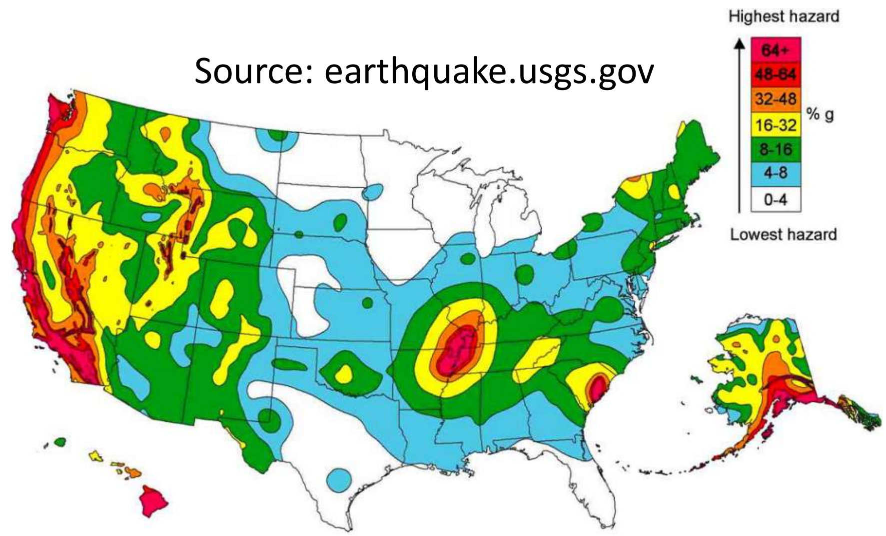
Chapter 3:
Ongoing and Future Research

Non-Uniform Risk Probability



Source: earthmagazine.org

Source: earthquake.usgs.gov



- ✓ Info from various sources (i.e., geology, climatology, transportation, and environmental science) should be used to determine probability
- ✓ Equipment failure probability due to disasters depends on distance to disaster epicenter, link length, intersection with disaster region

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Flexible Content-Connectivity Protection Plan

Customer:

- ✓Require content connectivity for set of nodes (e.g., offices)
- ✓Demand survivability against large-scale failures

Operator:

- ✓Must satisfy customer's requirements
- ✓Question: Fixed logical topology?

Flexible Content Connectivity Protection:

- ✓Optimally design (lowest cost) logical topology with options
- ✓Add more datacenters
- ✓Add more logical links

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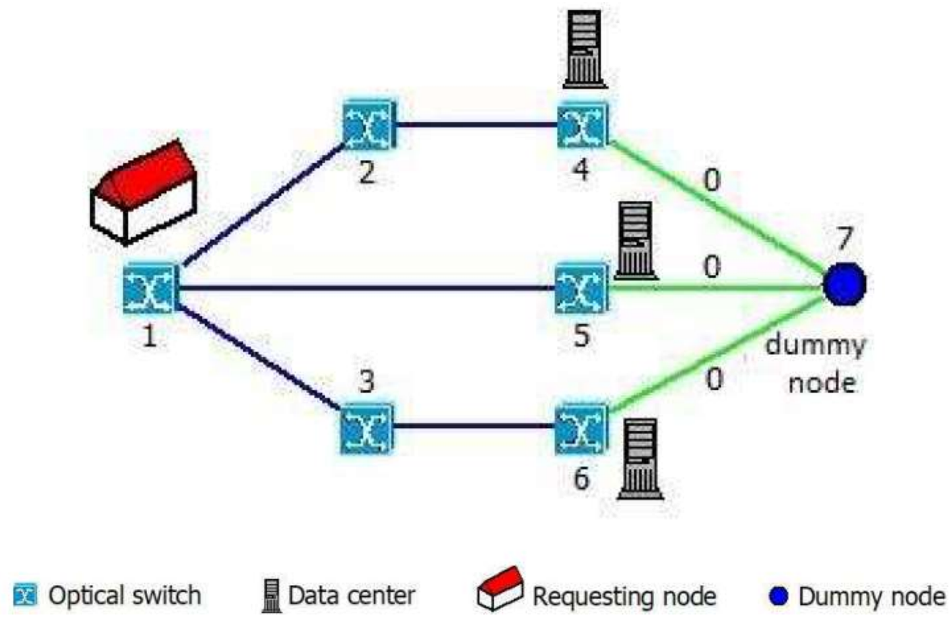
Dummy Node Approach for Content Connectivity

- CC-n: Find $n + 1$ link-disjoint paths from content-requesting node (node 1) to dummy node through datacenters
- We expect fast optimal solutions (higher scalability)



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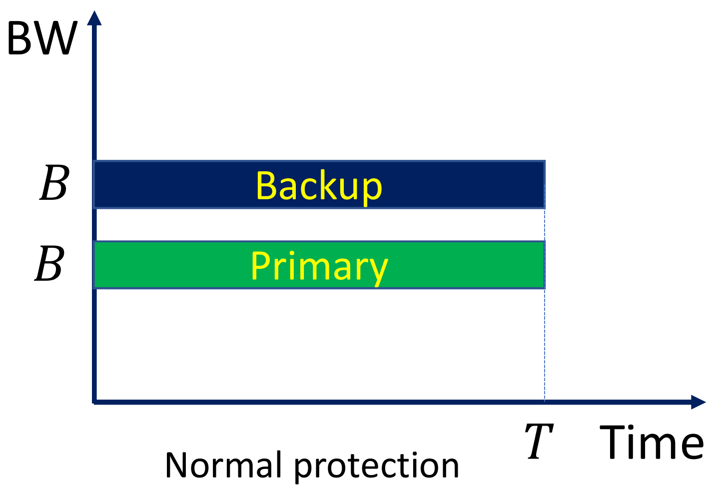
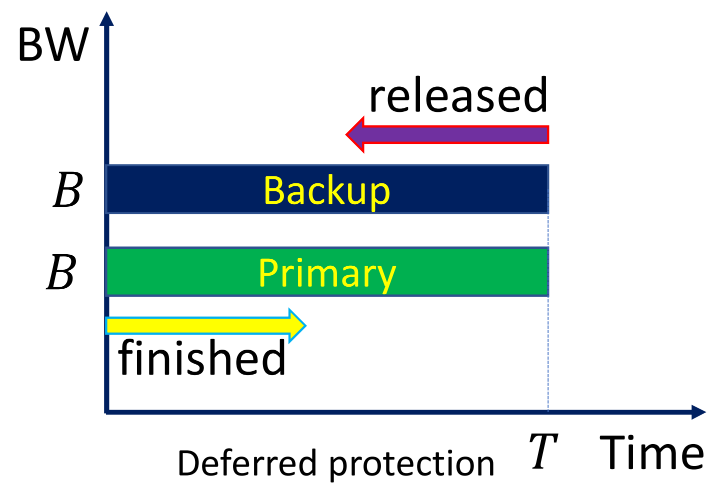
Deferred Protection for Content Connectivity

Major delay of a large file transmission: $\frac{Packet\ size}{Link\ BW} = \frac{L}{B} = T$ (s)

Do we need content connectivity protection for entire T?





✓ Save network resources

Acknowledgement

- NSF-JUNO2 CNS-1818972

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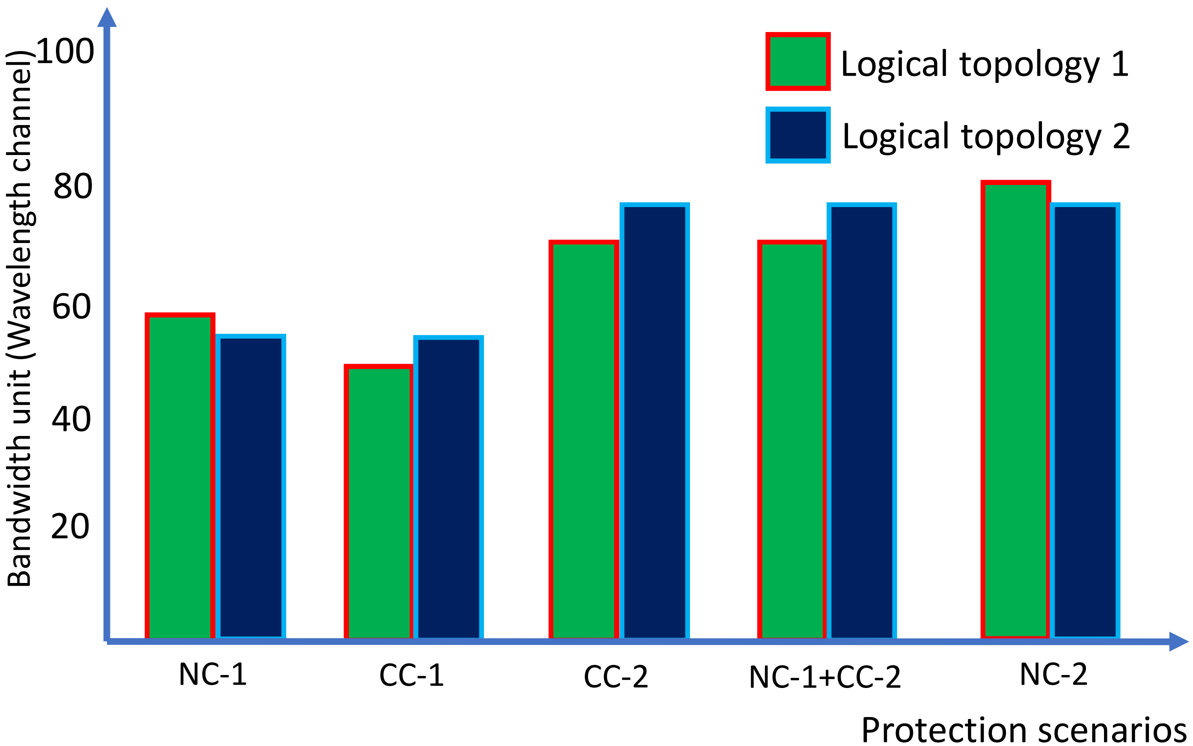
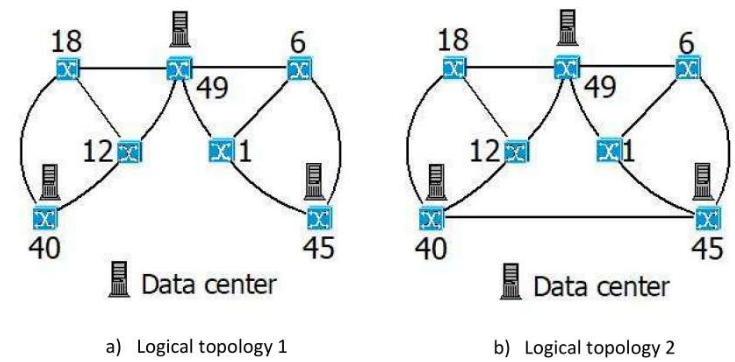
Why NC-1 (Topo 1) > NC-1 (Topo 2)?





Logical topologies

- ✓ 40-45 link makes topology hard to be disconnected
- ✓ 6 wavelength channels for 40-45
- ✓ But save 8 wavelength channels for other links taking shorter paths (less strict conditions)
- ✓ NC-1 (Topo 2): 2 wavelength channels less

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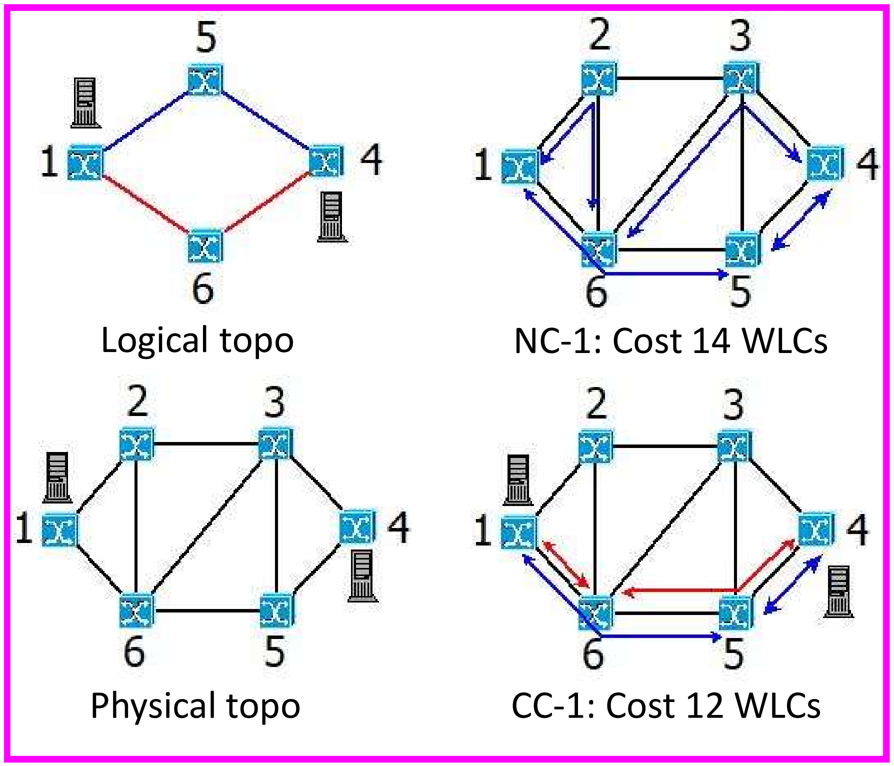
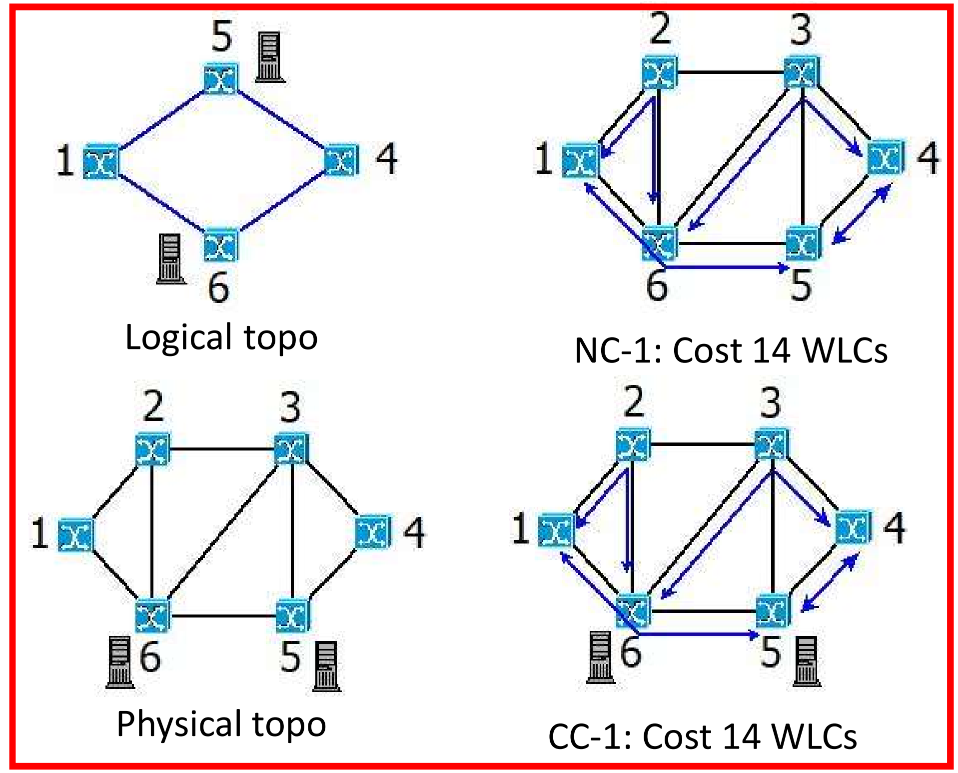
Scenarios Where NC = CC





- ✓ CC < NC
- ✓ DCs fanned out
- ✓ Overlapping (i.e., link 5-6)

- ✓ CC = NC
- ✓ DCs inner part

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