Content-connected Protection in Optical Networks: Definition, Classification, and Approaches

Computer Networks Lab Meeting

Friday, Aug. 09, 2019

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Outline

1. Content Connectivity (CC) as an additional metric for network survivability under disasters
2. Content-connected protection in optical networks
3. New approaches to the content connectivity problem

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CC as an additional network survivability metric

- Network Connectivity (NC, i.e. reachability of every network node from all other nodes) has been traditional metric for network survivability.
- NC is not always possible under disaster scenarios.
- With the shifting of service paradigm towards cloud computing/storage, some network services can be provided if a content replica is available in all disconnected network segments.
- Content Connectivity (CC, i.e. reachability of content from every node under failure scenarios) has been introduced as an additional metric for network survivability against disasters [2].

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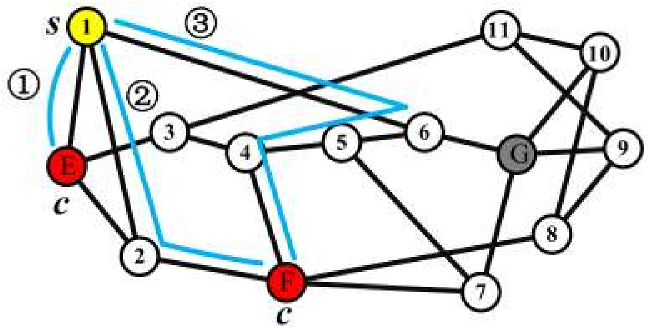
[2] M. F. Habib, M. Tornatore, and B. Mukherjee, “Fault-tolerant virtual network mapping to provide content connectivity in optical networks,” *Proc. IEEE/OSA Opt. Fiber Commun. Conf. (OFC13)*, Mar. 2013.

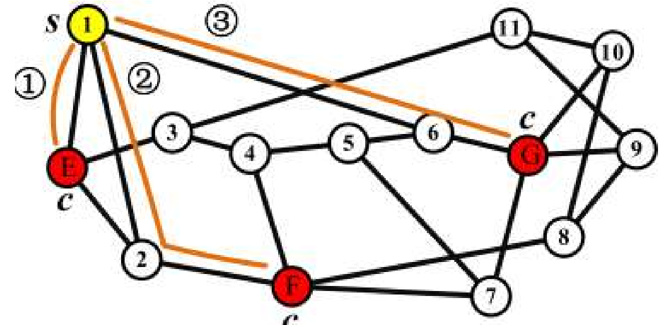
Content-connected Protection in Optical Networks

- Protection in Optical Layer (Layer 1)
- Protection in IP Layer (Layer 3)
- Multi-layer protection

Content-connected Protection in Optical Layer



a) Multiple logical links per datacenter



b) One logical link per datacenter

Fig. 1: CC protection in optical layer (layer 1) [1]

- Find physical link-disjoint paths from a node requiring content protection to datacenters
- Variation of Bhandari's and Suurballe's works

[1] X. Li *et al.*, "Content placement with maximum number of end-to-content paths in K-node (edge) content connected optical datacenter networks," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 9, no. 1, pp. 53-66, Jan. 2017.

Content-connected Protection in IP Layer

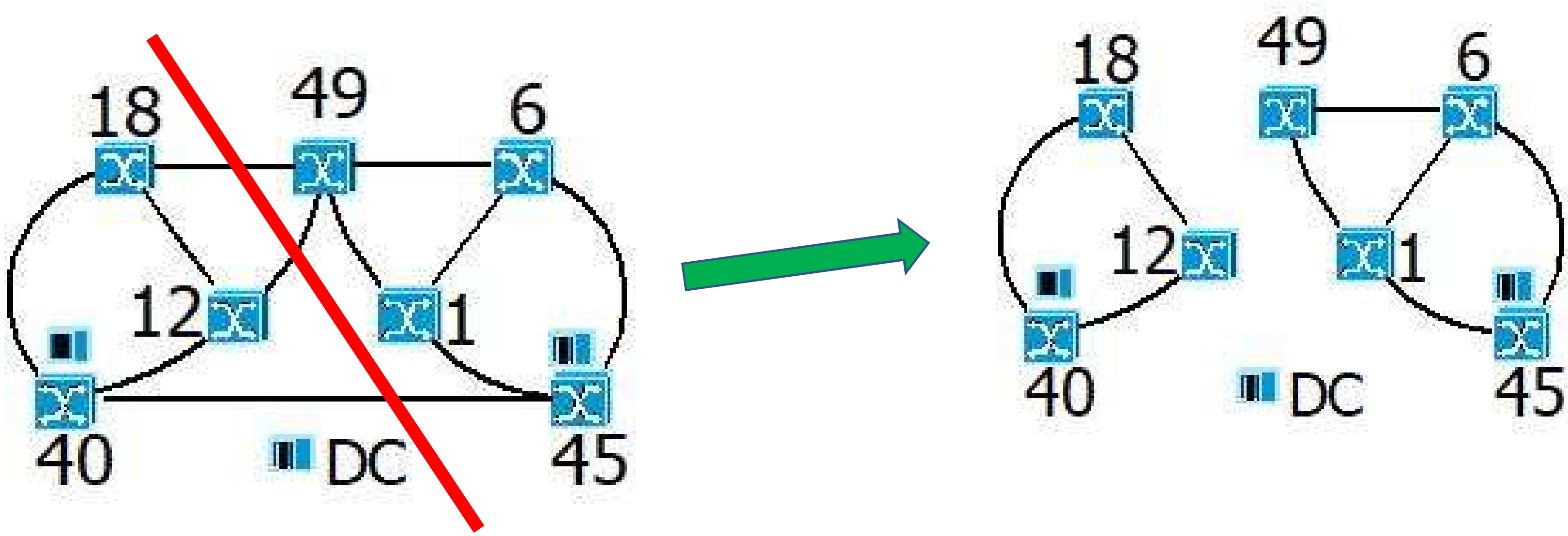


Fig. 2: Logical topology with DCs

- No direct optical links to DCs for nodes 49
- Node 49 can use either node 1 or 6 as transit nodes
- However, the logical topo is content-connected in IP layer (layer 3).

Protection in Multiple Layers

- Protection in both optical layer and IP layer
- IP connection A-C consists of two optical connections A-B and B-C.
- The dashed line protects the two optical connections (shared).
- The dotted/dashed line protects the IP connection.
- Coordination is required to avoid redundancy.
- Content connectivity with multilayer protection (long-termed)

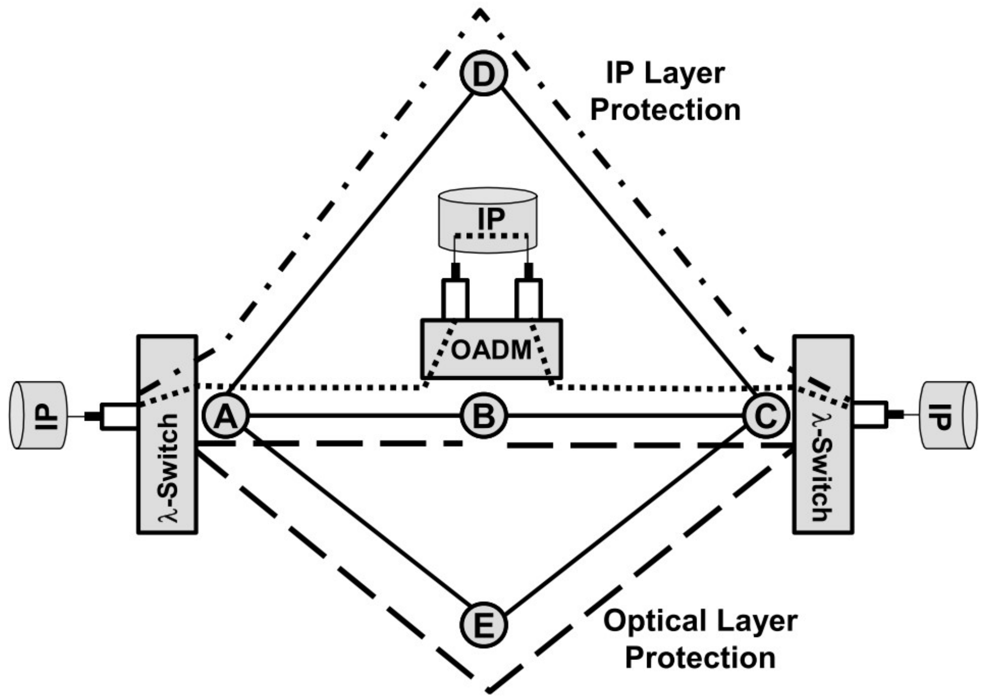


Fig. 3: Multi-layer protection in optical [4]

[4] J. M. Simmons, *Optical Network Design and Planning*. Springer, 2014.

Content Connectivity: What have been done?

- A fixed number of physical link failures: one or up to two
- Content protection in the optical layer [1]
- Content protection in the IP layer [2], [3]

[1] X. Li *et al.*, "Content placement with maximum number of end-to-content paths in K-node (edge) content connected optical datacenter networks," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 9, no. 1, pp. 53-66, Jan. 2017.
[2] M. F. Habib, M. Tornatore, and B. Mukherjee, "Fault-tolerant virtual network mapping to provide content connectivity in optical networks," *Proc. IEEE/OSA Opt. Fiber Commun. Conf. (OFC13)*, Mar. 2013.
[3] A. Hmaity, F. Musumeci, and M. Tornatore, "Survivable virtual network mapping to provide content connectivity against double-link failures," *Proc. 12th Conf. Design of Reliable Comm. Networks (DRCN)*, Mar. 2016.

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Content Connectivity: Previous Works' Limitations

- Networks are not well prepared for disaster scenarios due to a fixed number of physical link failures.
- Formulation scalability: applicable to small networks
- Heuristic algorithms: losing optimality

Content Connectivity: Low Scalability Problem

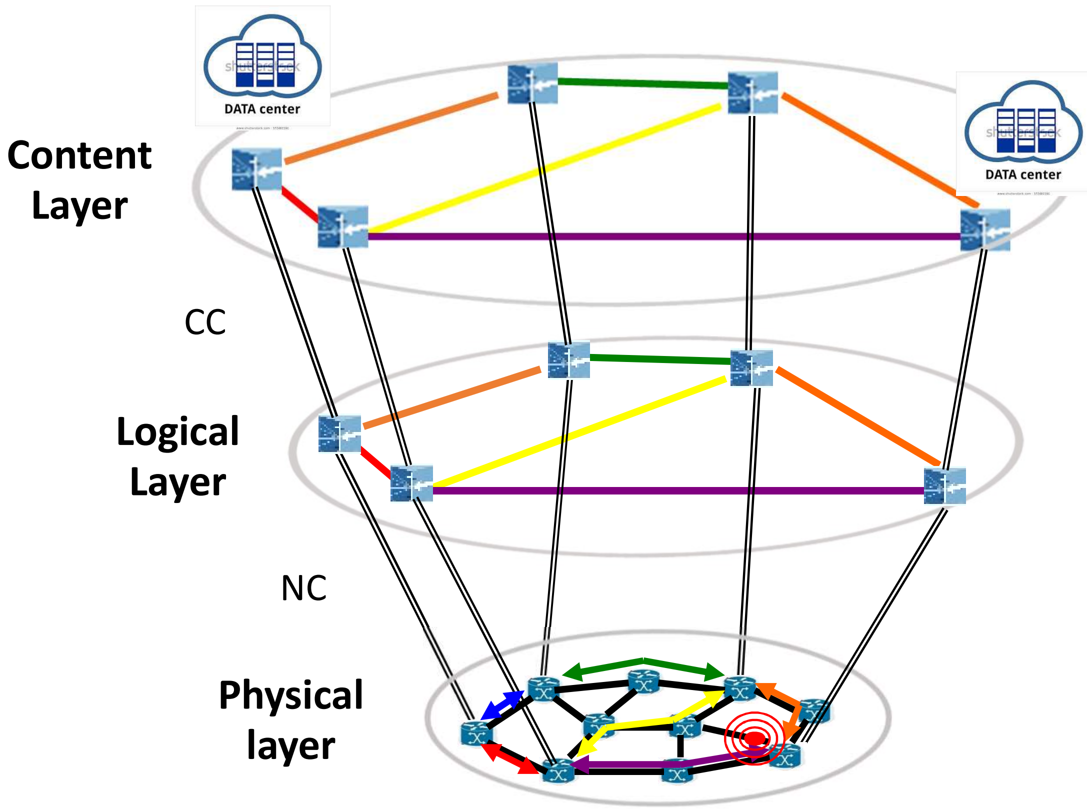

Fig. 4: Content protection in optical networks

- Flow conservation for logical links over the physical layer
- Flow conservation and survivability protection for the content layer over the logical and physical layers
- e.g. two physical link failures, the variable $X_{ij,kl}^{ud,st}$ has dimension of 8 (low scalability)

Content Connectivity: A New Approach

- What are interesting?
  - ✓Against arbitrary number of physical link failures, hence networks are better prepared for disaster scenarios
- Why it is hard?
  - ✓High scalability (nearly) independently of number of physical link failures
  - ✓Keeping optimality of the problem
- Solved!

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New Approach to CC Problem: Optical Protection

- Given:
  - ✓ $G_P(V_P, E_P)$
  - ✓ $G_L(V_L, E_L)$
  - ✓ $D \subset V_L$: DC set
  - ✓ n: number of physical link failures
  - ✓ $M = |D|$
  - ✓ $P_n = \{\{P_q\}\}$: the set of sets all n distinct physical links
- Variable:
  - ✓ $f_{ij}^{st} = 1$ if logical link st is mapped over physical link ij, 0 otherwise.
- Objective function:

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

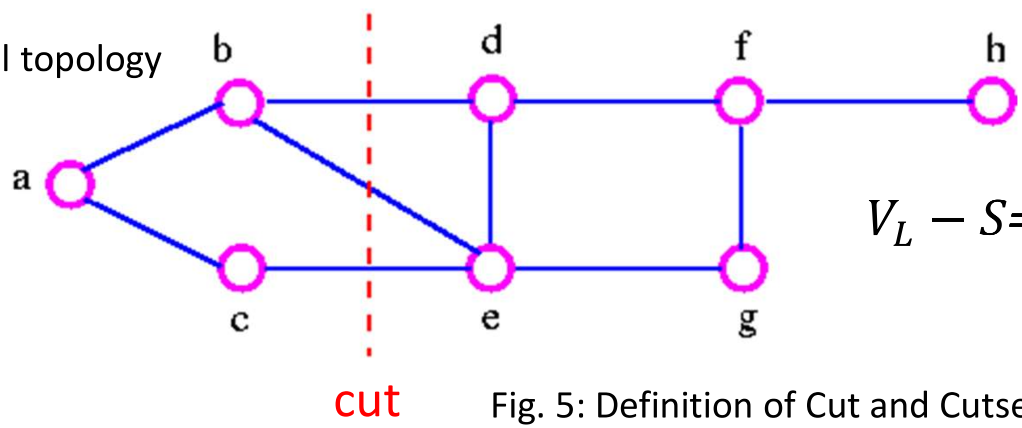
- Subject to:
  - ✓ Capacity constraint
  - ✓ Flow conservation
  - ✓ $\sum_{t \in D,\, ij \in P_q} f_{ij}^{st} \leq M - 1, \quad \forall P_q \in P_n, \forall s \in V_L - D$

New Approach to CC Problem: IP Layer Protection

- A *Cut*: the partition of a graph $G_L(V_L, E_L)$ into 2 disconnected parts, and divides V_L into two disjoint sets S and $V_L - S$
- A *Cutset*: the set of links with one endpoint in S and the other in $V_L - S$
- Menger's theorem: removal of all links in a cutset disconnects the graph.

Logical topology

$S = \{a, b, c\}$



$V_L - S$= {*d, e, f, g, h*}

Fig. 5: Definition of Cut and Cutset

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New Approach to CC Problem: IP Layer Protection

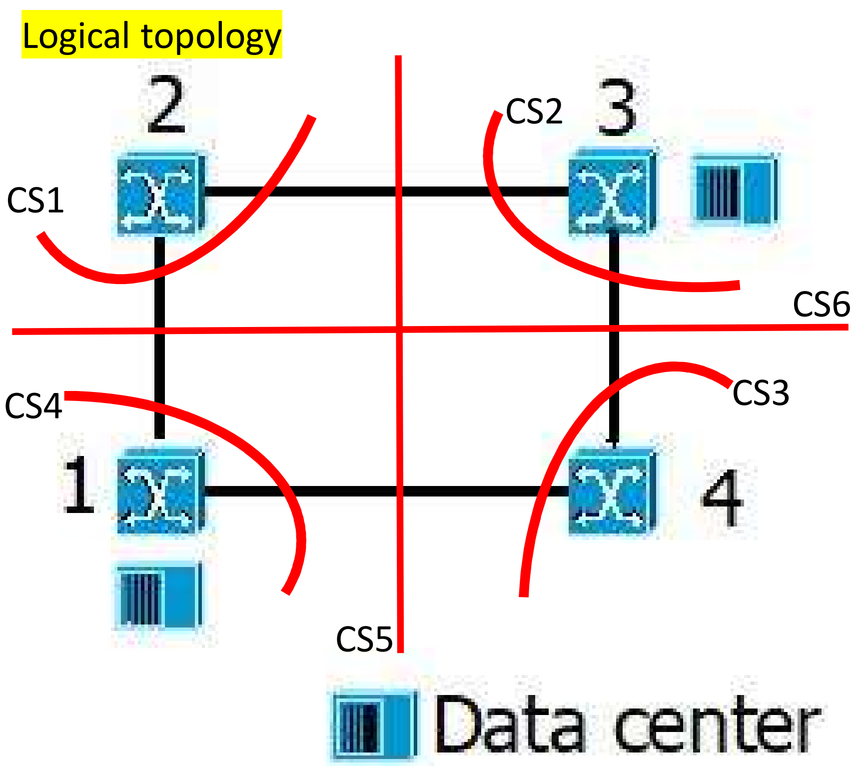

Fig. 6: Definition of content-connected cutset

- There are total 6 *cutsets*.
- If cutsets either CS1 or CS3 is mapped over the same physical link, no content connectivity against single-link failures (CC-1).
- Generalized, do not map/route all logical links in CS1 and CS3 over n distinct physical links, CC-n is ensured.

Note: NC-*n*: Network Connectivity; CC-*n*: Content Connectivity; *n*: number of physical link failures

New Approach to CC Problem: IP Layer Protection

- Necessary conditions for CC-n existence:

Theorem 1. *Given $G_P(V_P, E_P)$, $G_L(V_L, E_L)$, and $D \subset V_L$, 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 $\delta(i) \geq n + 1$.*

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New Approach to CC Problem: IP Layer Protection

- CC-n enforcement:

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

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

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New Approach to CC Problem: Math. Formulation

Inputs and variables

- $G_P(V_P, E_P), G_L(V_L, E_L), n, D, \mathcal{P}_n, C_{CC}$, and f_{ij}^{st} have been introduced in Section II.
- W is the number of wavelengths per physical link.
- F_{ij} is the number of fibers on the physical link ij.

Objective function

$$\min \sum_{ij \in E_P,\ st \in E_L} f_{ij}^{st} \quad (1)$$

Subject to:

$$\sum_{st \in E_L} f_{ij}^{st} \leq F_{ij} \times W, \quad \forall ij \in E_P \quad (2)$$

$$\sum_{j:ji \in E_P} f_{ji}^{st} - \sum_{j:ij \in E_P} f_{ij}^{st} = \begin{cases} -1 & \text{if } i = s \\ 1 & \text{if } i = t \\ 0 & \text{otherwise} \end{cases}, \quad \forall i \in V_P, \forall st \in E_L \quad (3)$$

$$\sum_{\substack{ij \in P_n^k \\ st \in C_{CC}^l}} f_{ij}^{st} \leq |C_{CC}^l| - 1, \ \forall P_n^k \in \mathcal{P}_n, \ \forall C_{CC}^l \in C_{CC} \quad (4)$$

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New Approach to CC Problem: Num. Results

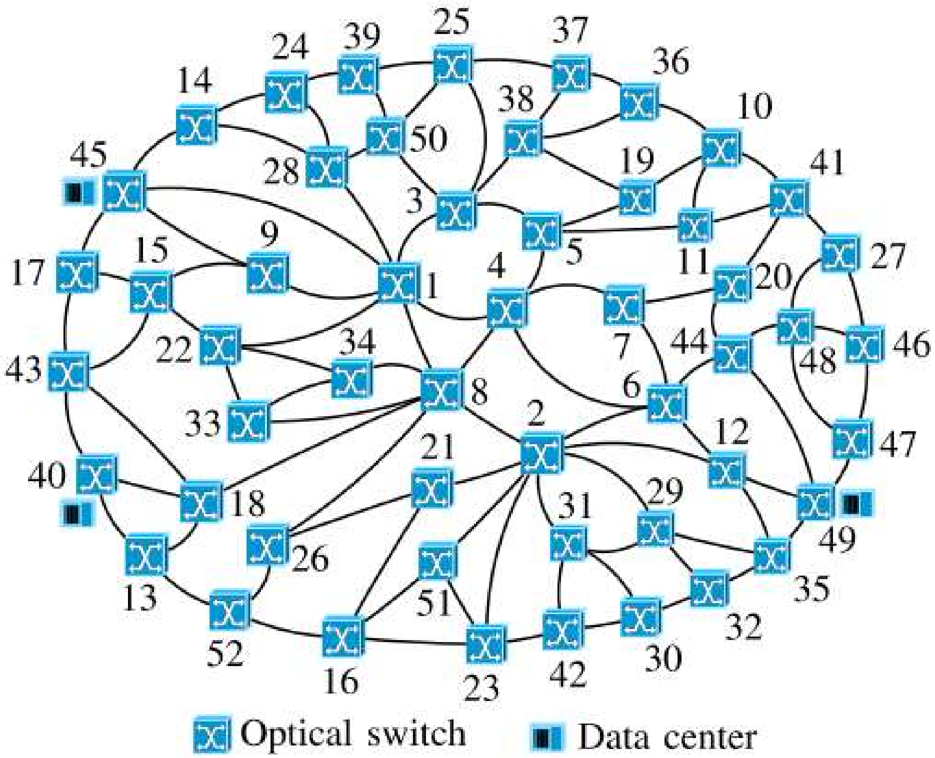

Fig. 7: Numerical example: physical topology

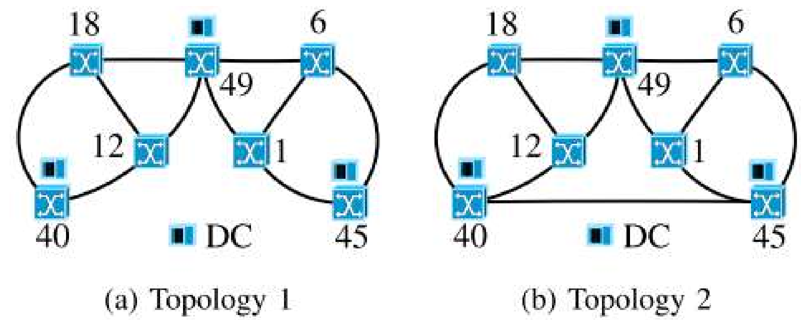

Fig. 8: Numerical example: logical topologies

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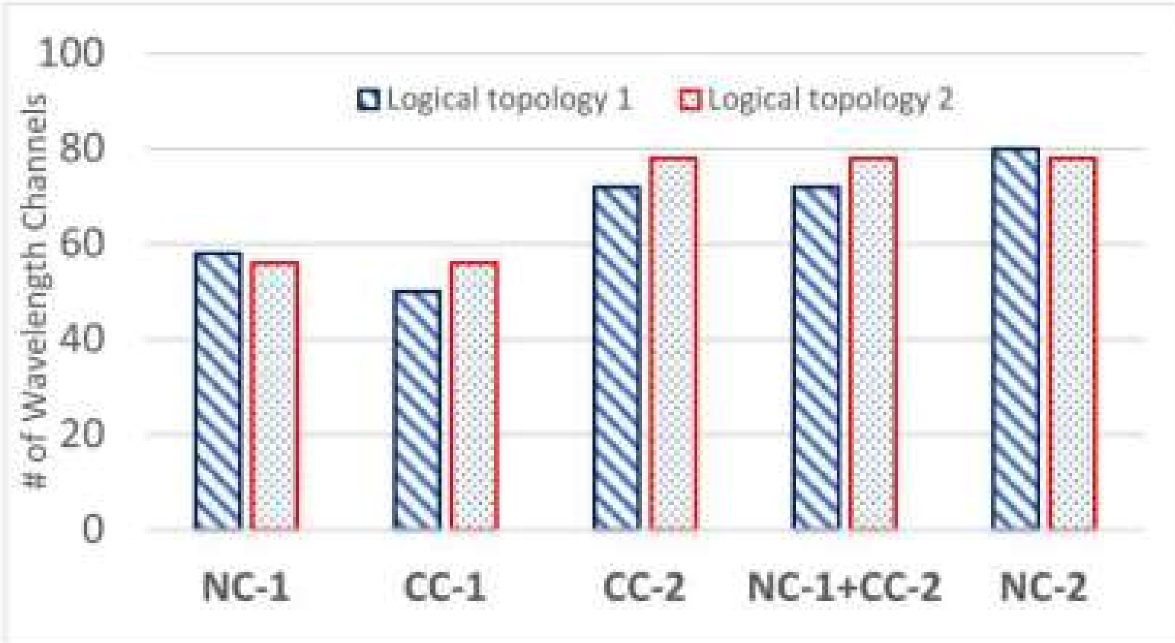
New Approach to CC Problem: Scalability Comparison

TABLE I: Complexity Comparison, Logical topology 1

Scenarios	Previous works		This work	
	# Var.	# Constr.	# Var.	# Constr.
NC-1	3,920 [5]	31,932 [5]	3,920	31,932
CC-1	90,220 [2]	90,423 [2]	3,920	13,116
CC-2	8,116,420 [3]	64,297,083 [3]	3,920	1,153,836
NC-1+CC-2	8,116,420 [3]	64,297,083 [3]	3,920	1,178,532
NC-2	NA	NA	3,920	4,822,956

[2] M. F. Habib, M. Tornatore, and B. Mukherjee, "Fault-tolerant virtual network mapping to provide content connectivity in optical networks," *Proc. IEEE/OSA Opt. Fiber Commun. Conf. (OFC13)*, Mar. 2013.
[3] A. Hmaity, F. Musumeci, and M. Tornatore, "Survivable virtual network mapping to provide content connectivity against double-link failures," *Proc. 12th Conf. Design of Reliable Comm. Networks (DRCN)*, Mar. 2016.
[5] 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.

New Approach to CC Problem: Num. Results



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New Approach to CC Problem: Extension

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

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***Abstract*—Network connectivity has been the traditional metric for network survivability against failures. In case of a disaster, network connectivity may not always be guaranteed due to multiple link failures. With the shifting service paradigm towards cloud computing/storage, some network services can still be provided if a content replica is available in all disconnected network segments. As a result, content connectivity has been introduced as an additional metric for network survivability under disasters. Content connectivity is defined as the reachability of content from every node in a logical topology under a given failure scenario. In this paper, we investigate the content connectivity problem in optical metro networks in the case of multiple (n) link failures. We consider the problem of mapping a logical topology over an optical metro network such that every node in the logical topology can reach at least one data center hosting the content after $n-$link failures. We formulate the problem as an integer linear program to minimize total network resource usage. We provide a cost comparison between content connectivity and network connectivity under various typical failure scenarios.**

***Index Terms*—Content connectivity, optical metro networks, data centers, survivable mapping, $n-$link failures**

(CC) has been introduced as an additional metric to measure network survivability [2]. CC is defined as the reachability of content from every node in a logical topology under failure scenarios. This metric is considered useful under large-scale failures as disasters, while NC will probably remain the default choice for smaller failure scenarios (as single failures).

Some research on CC has already been conducted. In [2], the authors solved the CC problem against single-link failures. In [3], the authors extended the CC problem to double-link failure scenarios. In both works, the CC problem was examined for backbone optical networks with mesh topologies.

In this work, we address the more general problem of CC against $n-$link failures focusing on optical metro networks where the physical topology consists of interconnected rings. We aim to provide protection to a logical topology mapped over a physical optical network. Our contributions can be summarized as follows. First, we propose a problem formulation that is more scalable than the ones in [2] and in [3].

- This work has been submitted to ANTS 2019.
- Extensions being considered:
  - ✓ Shared content protection between among logical topologies
  - ✓ Diverse traffic and link capacity
  - ✓ Generalize the scenarios in which: a) CC cost is lower than NC cost, b) CC cost is equal to NC cost, c) NC is not possible but CC can be guaranteed.
  - ✓ If the logical topology is not fixed, which way with minimal cost to provide CC-n (more links or more DCs).

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