Survivable Lightpath Mapping for Content and Network Connectivity against Single-link and Double-link Failures

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January 25, 2019

Disaster-Resiliency Strategies for NG MONs

Key terms and Project Objectives

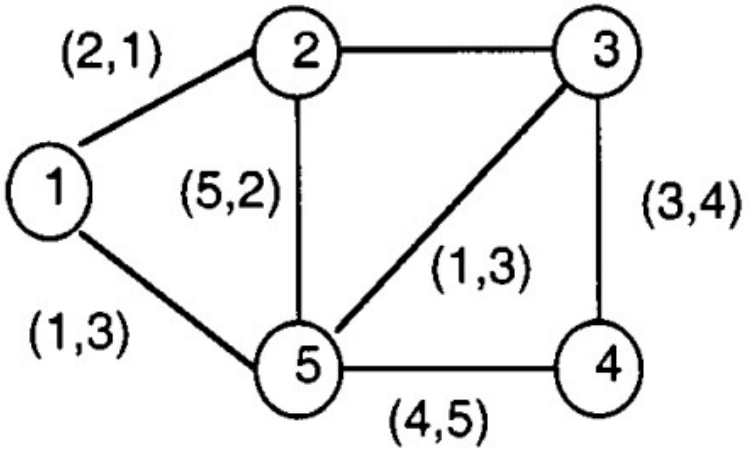
- ✓**ultra-reliable**, **low-latency** services (autonomous driving, augmented reality, telemedicine), **resilient** against largely-disruptive events
- ✓enable technologies: network-and-computing ecosystem, SDN, Edge Computing, and Slice Networking (NFV)

Research directions: (might be explored in order)

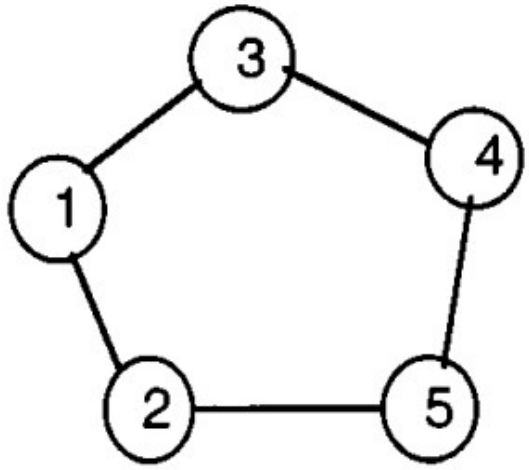
- ✓disaster-resilient **control plane** in NG-MAN: cognitive and hierarchical control plane that remains operational even main controllers fails
- ✓slicing protection for disaster-resilient NG-MAN **data plane**
- ✓rapid **recovery** during post-disaster phase

Survivable Lightpath Mapping in WDM

- **Logical topology**: a set of nodes and lightpaths connecting the nodes
- **Physical topology:** a set of nodes and fibers connecting the nodes
- **Question:** How to map a logical topology to a given physical topology so the logical topology can be connected after physical link failures



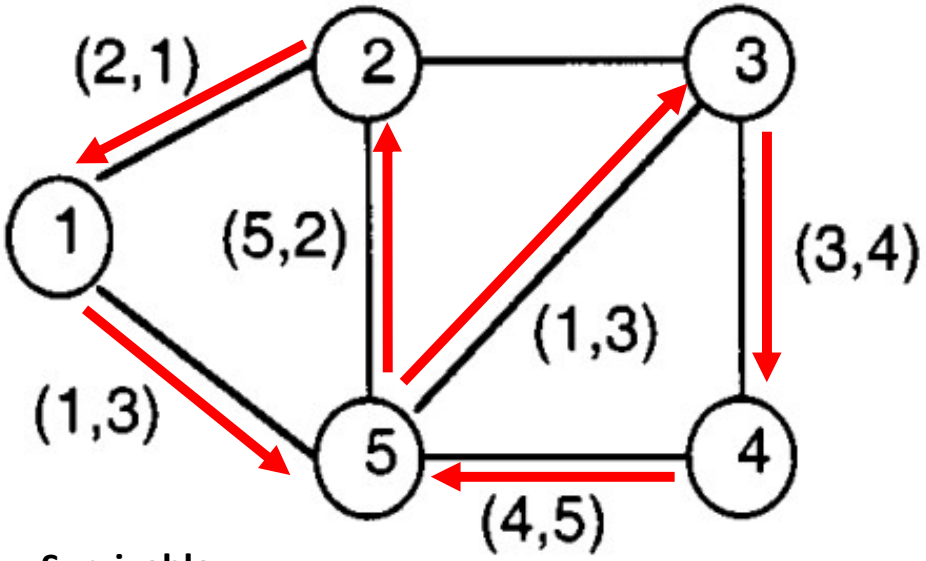
Physical Topology



Logical Topology

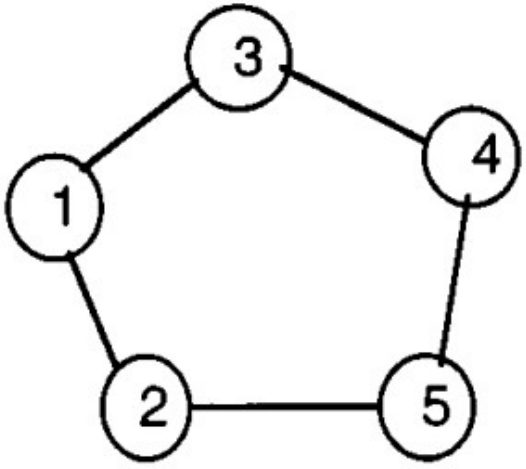
[1] E. Modiano and A. Narula-Tam, "Survivable lightpath routing: a new approach to the design of WDM-based networks," in *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 4, pp. 800-809, May 2002.

Survivable Lightpath Mapping in WDM



Survivable

Physical Topology



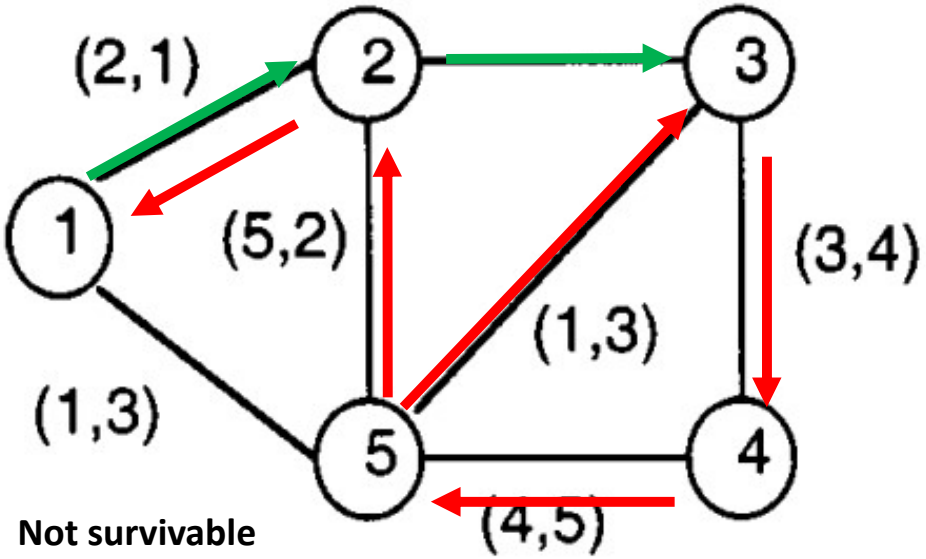
Logical Topology

No physical links support more than one logical connection

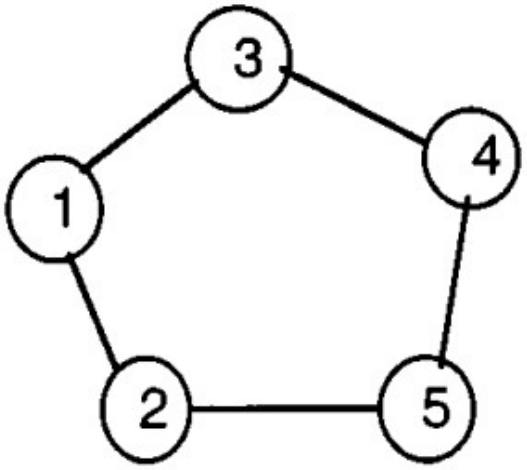
- ✓ In this case, the logical topology is a ring
- ✓ 2-connected or resilient against a single-link logical failure

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

Survivable Lightpath Mapping in WDM



Physical Topology



Logical Topology

- ✓ Many logical topologies, no survivable mappings can be found
- ✓ NP-complete problems

- ✓ In this case, the logical topology is a ring
- ✓ 2-connected or resilient against a single-link logical failure

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Notions, Assumptions, Lemma, and Theorems

- ✓Let define: a physical topology consist of:
  - *N* nodes *(1,2,…N)*
  - A set of edges *E* where (i, j) is in *E* if a link exists between node *i* and node *j*
  - Bidirectional physical links
- ✓Logical topology consist of:
  - N_L logical nodes
  - E_L logical edges and edge *(s,t)* is in E_L if both *s* and *t* are in N_L and there exists a logical link between them
- ✓A *cut* divides *N* nodes in to two parts *S* nodes and *(N-S)* nodes
- ✓A ***cut-set*** is a **set of edges** that have one endpoint in *S* and the other in (*N-S),* notes as *CS(S,N-S)*

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

Notions, Assumptions, Lemma, and Theorems

✓**Lemma 1**: Menger's Theorem

A **logical** topology with set of nodes N_L and set of edges E_L is 2-connected *if and only if* every nontrivial *cut (S, N_L-S)* has a corresponding **cut-set** of size **greater than or equal to 2**.

✓**Theorem 1:**

- A routing is survivable if and only if for every cut-set *CS(S, N_L-S)* of the logical topology the following holds. Let *E(s,t)* be the set of physical links used by logical link *(s, t).* Then, for every cut-set *CS(S, N_L-S)*

$$\cap E(s,t) = \varnothing$$

$$(s,t) \in \mathrm{CS}(S, N_L - S).$$

- **In other words**, not all of the logical links belonging to a cut-set can be routed on the same physical link.

✓**Theorem 2**: Survivable routing problem is NP-complete.

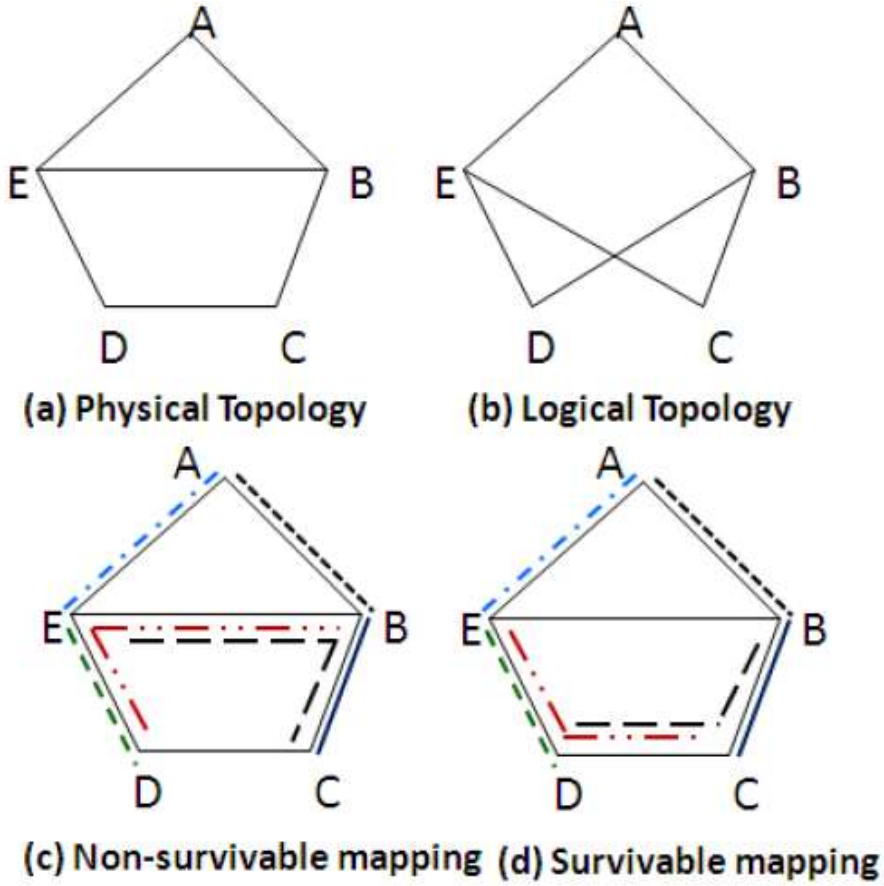
[1] E. Modiano and A. Narula-Tam, "Survivable lightpath routing: a new approach to the design of WDM-based networks," in *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 4, pp. 800-809, May 2002.

How Survivable Mapping applied to Network Resilience

- ✓**Network connectivity:** reachability of every network node from all other nodes
- **Content connectivity:** reachability of every content from any point of a network
- **An overlay network:** a virtual/logical network
- **Virtual network mapping:** the assignment of a virtual network to a physical network
- **Virtual links:** optical lightpaths
- **Objectives:**
  - ✓Maintain content connectivity
  - ✓Minimize network resources

M. F. Habib, M. Tornatore, and B. Mukherjee, "Fault-Tolerant Virtual Network Mapping to Provide Content Connectivity in Optical Networks," in *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013*, OSA Technical Digest (online) (Optical Society of America, 2013), paper OTh3E.4.

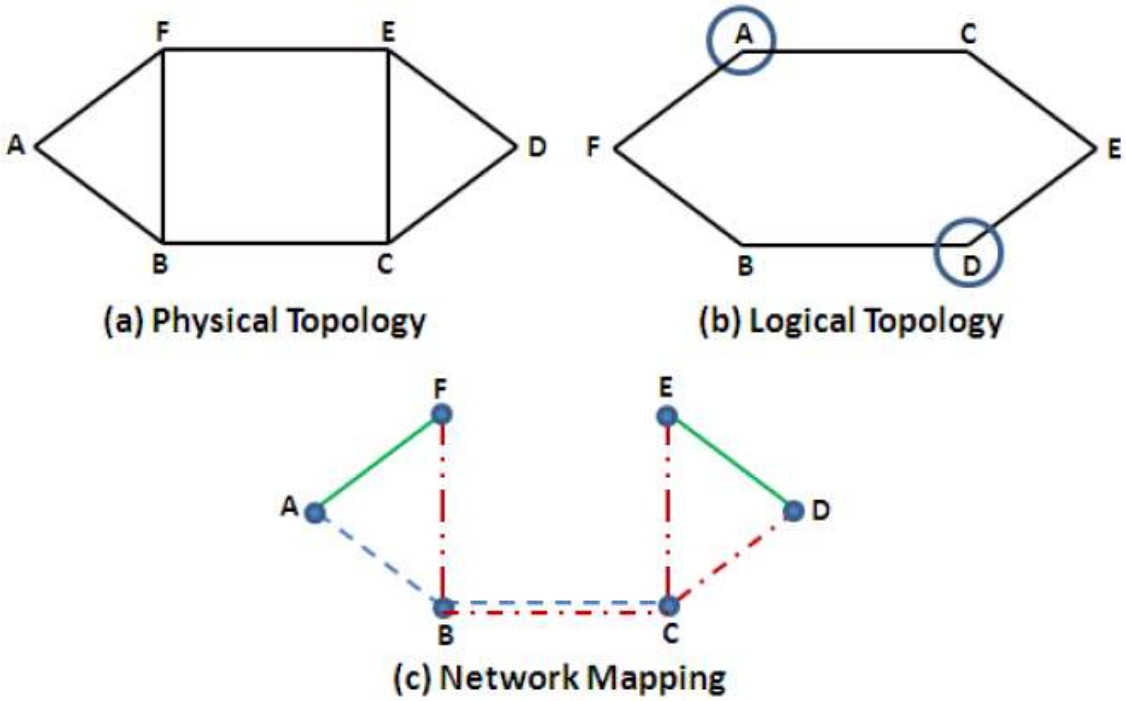
Survivable mapping: single link failure



- ✓Physical topology: real links + nodes
- ✓ Virtual topology to be mapped to the physical one
- ✓In (c), **if ED link fails**, logical paths ED and BD are disconnected (content in D is unreachable).
- ✓In (d), BD = BC-CD; EC = ED-DC, there is no single physical link failure making the network disconnected.

[2] M. F. Habib, M. Tornatore, and B. Mukherjee, "Fault-Tolerant Virtual Network Mapping to Provide Content Connectivity in Optical Networks," in *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013*, OSA Technical Digest (online) (Optical Society of America, 2013), paper OTh3E.4.

Survivable mapping: single link failure



- Logical link mappings:
  - ✓ AF = AF
  - ✓ AC = AB-BC
  - ✓ BF = BF
  - ✓ BD = BC-CD
  - ✓ DE = DE
  - ✓ CE = CE
- If a content is distributed at A and D, content connectivity is guaranteed.
- The problem is formulated as an ILP problem to map logical links to physical ones, place content, and minimize network resources.
- Both scenarios, efficient for **single link failure**

[2] M. F. Habib, M. Tornatore, and B. Mukherjee, "Fault-Tolerant Virtual Network Mapping to Provide Content Connectivity in Optical Networks," in *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013*, OSA Technical Digest (online) (Optical Society of America, 2013), paper OTh3E.4.

Survivable mapping: double-link failure

2016 12th Int. Conference on the Design of Reliable Communication Networks (DRCN 2016)

Survivable Virtual Network Mapping to Provide Content Connectivity Against Double-Link Failures

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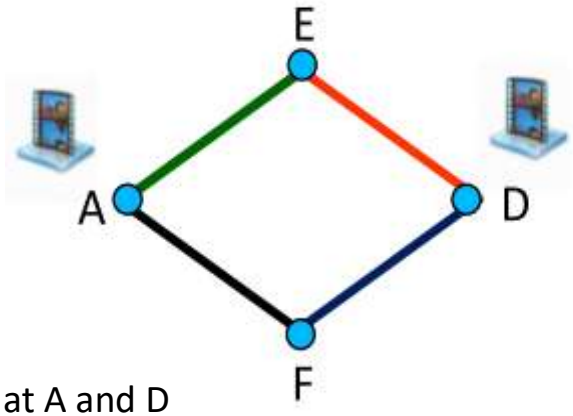
- **Main contributions:**
  - ✓**Content connectivity** after a double-link failure
  - ✓**Network connectivity** after a single-link failure **and content connectivity** after a double-link failure

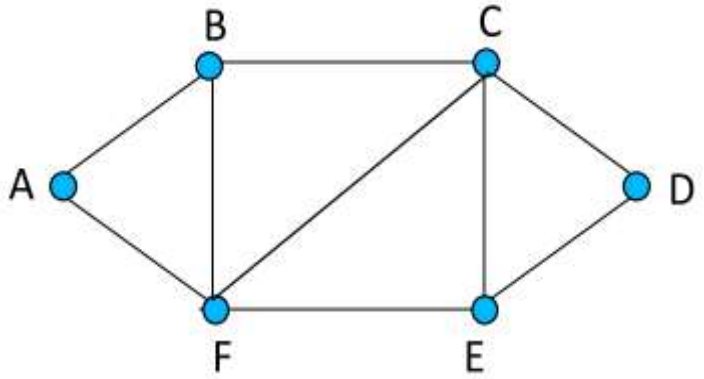
[3] A. Hmaity, F. Musumeci and M. Tornatore, "Survivable virtual network mapping to provide content connectivity against double-link failures," *2016 12th International Conference on the Design of Reliable Communication Networks (DRCN)*, Paris, 2016, pp. 160-166.

Survivable mapping: double-link failure



Data centers at A and D

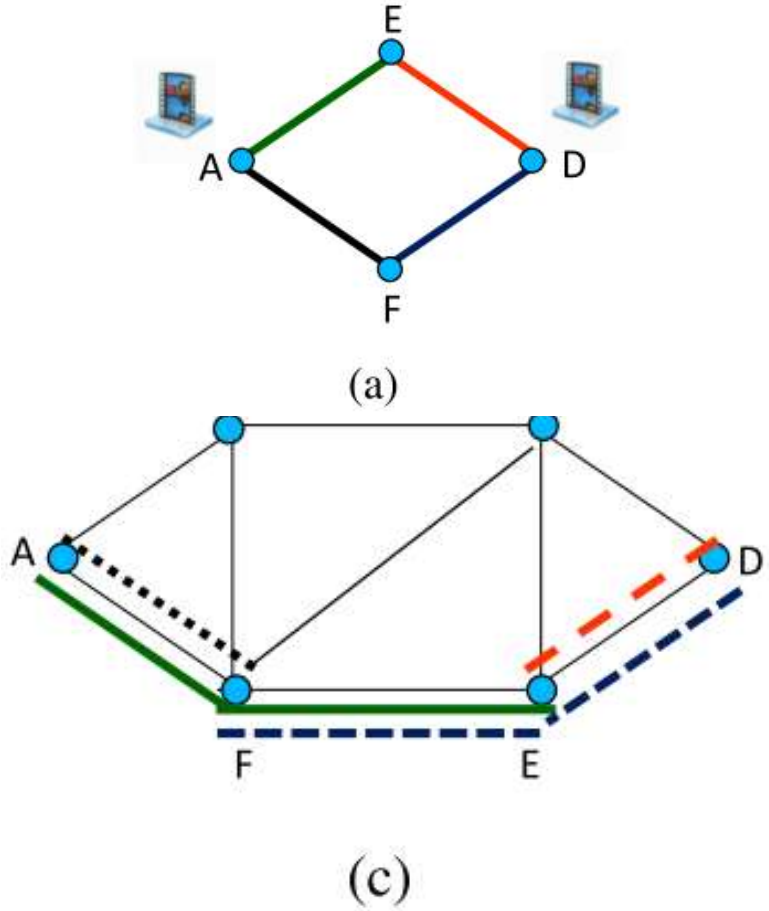
(a)
Virtual topology



(b)
Physical topology

[3] A. Hmaity, F. Musumeci and M. Tornatore, "Survivable virtual network mapping to provide content connectivity against double-link failures," *2016 12th International Conference on the Design of Reliable Communication Networks (DRCN)*, Paris, 2016, pp. 160-166.

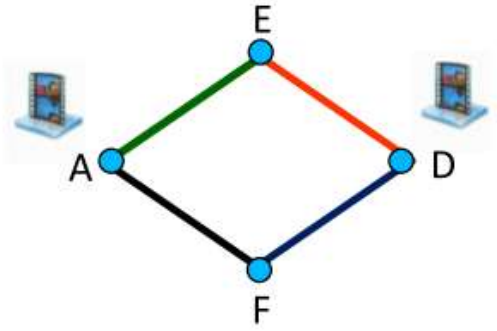
Non-survivable mapping



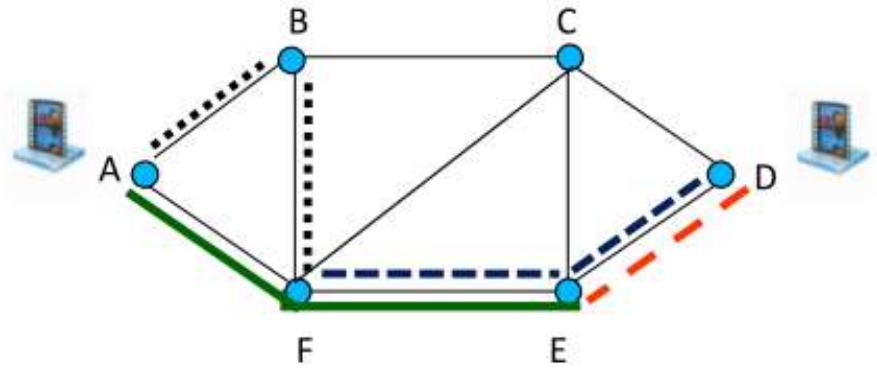
- In case the physical link FE fails, the logical links AE and DF are disconnected
- Network connectivity is not guaranteed because not content replication in A and D

[3] A. Hmaity, F. Musumeci and M. Tornatore, "Survivable virtual network mapping to provide content connectivity against double-link failures," *2016 12th International Conference on the Design of Reliable Communication Networks (DRCN)*, Paris, 2016, pp. 160-166.

Content-connected survivable mapping



(a)

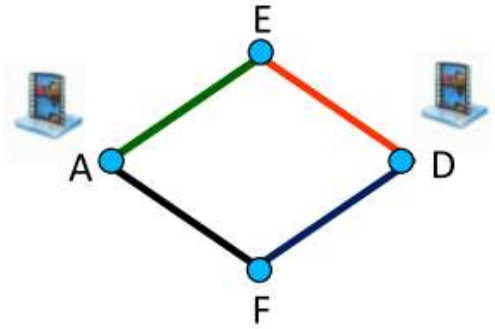


(d)

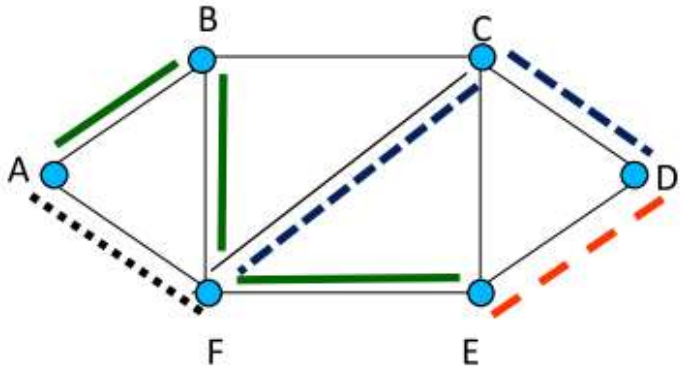
- In case the physical link FE fails, the logical links AE and DF are disconnected
- Content connectivity is guaranteed due to the replication in A and D

[3] A. Hmaity, F. Musumeci and M. Tornatore, "Survivable virtual network mapping to provide content connectivity against double-link failures," *2016 12th International Conference on the Design of Reliable Communication Networks (DRCN)*, Paris, 2016, pp. 160-166.

Network-connected survivable mapping



(a)

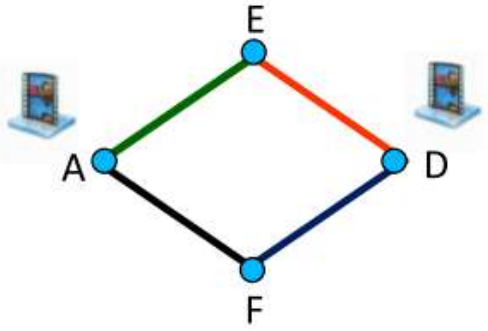


(e)

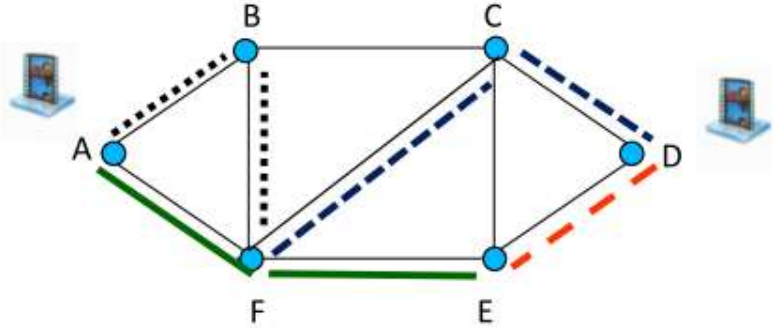
- In case the physical link FE fails, network connectivity is guaranteed.

[3] A. Hmaity, F. Musumeci and M. Tornatore, "Survivable virtual network mapping to provide content connectivity against double-link failures," *2016 12th International Conference on the Design of Reliable Communication Networks (DRCN)*, Paris, 2016, pp. 160-166.

Content-connected survivable mapping



(a)



(f)

- In case the physical links FE and AE fail (double-link failure), content connectivity is still guaranteed.

[3] A. Hmaity, F. Musumeci and M. Tornatore, "Survivable virtual network mapping to provide content connectivity against double-link failures," *2016 12th International Conference on the Design of Reliable Communication Networks (DRCN)*, Paris, 2016, pp. 160-166.

Approaches in the three papers

- ✓The problem of survivable mapping/routing and content placement is formulated as an Integer Linear Programing (ILP) problem.
- ✓Limit on **scalability**
- ✓**Proposal**: Develop a heuristic algorithm for network and content connectivity (in progress)

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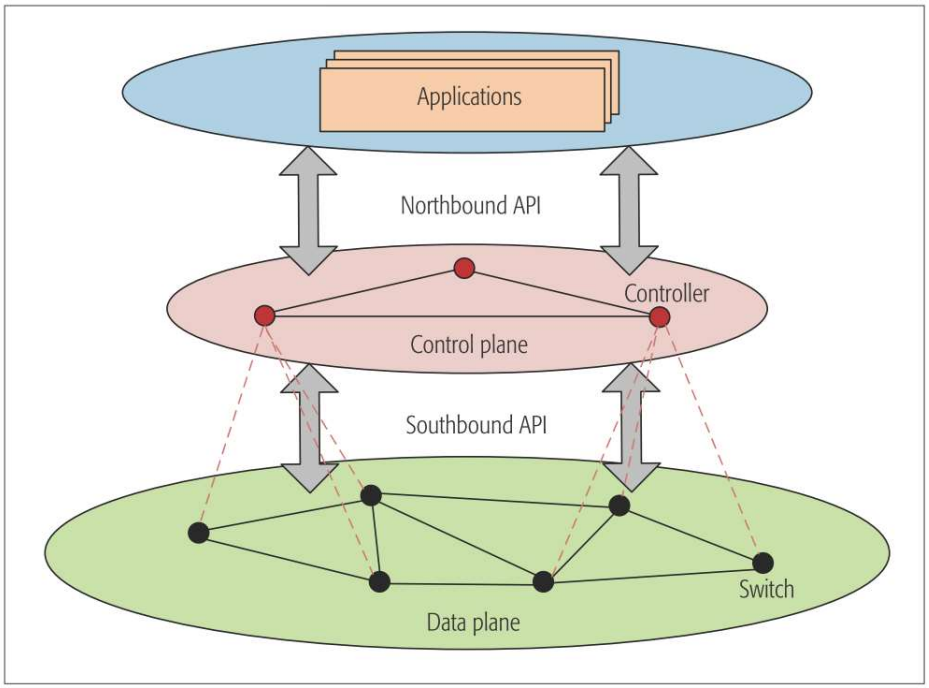
Research Tasks proposed in the Project

- Research Task 3: Scalable algorithms for disaster-resilient content-connected slice mapping (UC Davis). Our previous work [48] modeled this problem by ILP. But ILPs have scalability limits, and today there are no scalable algorithms for this problem. The development of a scalable heuristic will leverage our knowledge on VN mapping based on meta-heuristics like genetic algorithms, and graph theoretic algorithms as SMART [94]. Latency constraint will be considered.

Note: I may ask Prof. Tornatore for the titles of the references [48] and [94]

Survivable mapping in Optical SDNs



- ✓ Multiple controllers for scalability, resilience, and reachability
- ✓ **Proposed studies:**
  - ➢ Content connectivity for controllers
  - ➢ Network connectivity between switches and controllers
- ✓ Next steps: define ILP problems and constraints (not fully understood some equations in the papers)

Thank you for your attention!

Questions and Comments