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

Computer Networks Lab Meeting
Friday, Aug. 09, 2019
Student: Giap Le
Supervisors: Prof. Mukherjee and Prof. Tornatore
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
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].

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

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

Content-connected Protection in IP Layer

- 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).

Fig. 2: Logical topology with DCs
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]

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]

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

- 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)

Fig. 4: Content protection in optical networks
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!
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
  \[ \sum_{t \in D, ij \in P_q} f_{ij}^{st} \leq M - 1, \forall P_q \in P_n, \forall s \in V_L - D \]
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.

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

$V_L - S = \{d, e, f, g, h\}$
New Approach to CC Problem: IP Layer Protection

• 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 $D \subseteq V_L$, 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 $\delta(i) \geq n + 1$. 
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 \(C_{CC} = \{C_{CC}^l(S_l, V_L - S_l) : S_l \cap D = \emptyset\}\) 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

\[
\sum_{ij \in P_n^k, st \in C_{CC}^l} f_{ij}^{st} \leq |C_{CC}^l| - 1, \ \forall P_n^k \in \mathcal{P}_n, \ \forall C_{CC}^l \in C_{CC}.
\]
New Approach to CC Problem: Math. Formulation

**Objective function**

$$\min \sum_{i,j \in E_P, s,t \in E_L} f_{ij}^{st}$$  \hspace{1cm} (1)

**Subject to:**

$$\sum_{s,t \in E_L} f_{ij}^{st} \leq F_{ij} \times W, \hspace{0.5cm} \forall i,j \in E_P$$  \hspace{1cm} (2)

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

$$\sum_{i,j \in P^k_n, s,t \in C_{CC}^l} f_{ij}^{st} \leq |C_{CC}^l| - 1, \hspace{0.5cm} \forall P^k_n \in P_n, \forall C_{CC}^l \in C_{CC}$$  \hspace{1cm} (4)

**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 $ij$. 
New Approach to CC Problem: Num. Results

Fig. 7: Numerical example: physical topology

Fig. 8: Numerical example: logical topologies
New Approach to CC Problem: Scalability Comparison

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Previous works</th>
<th></th>
<th>This work</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># Var.</td>
<td># Constr.</td>
<td># Var.</td>
<td># Constr.</td>
</tr>
<tr>
<td>NC-2</td>
<td>NA</td>
<td>NA</td>
<td>3,920</td>
<td>4,822,956</td>
</tr>
</tbody>
</table>


New Approach to CC Problem: Num. Results
New Approach to CC Problem: Extension

• 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).