Content Accessibility in Optical Cloud Networks Under Targeted Link Cuts

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COST Action 15127
Resilient Communication Services Protecting End-User Applications from Disaster-Based Failures

- WG 1: Large-scale natural disasters
- WG 2: Weather-based disruptions
- WG 3: Technology-related disruptions
- WG 4: Malicious human activities
  - How to quantify network vulnerability to attacks?
  - How to measure the level of difficulty for an attacker to affect the network?
Outline

• Introduction
• Content Delivery Networks
• Gauging CDN Robustness
  • Average Two-Terminal Reliability
  • Average Content Accessibility
• Simulation results
• Conclusions
Introduction

• Immense growth of the amount and variety of network traffic[1]
• Intensive growth of data center traffic and cloud computing[2]
  • Annual global data center traffic will reach 10.4 zettabytes by 2019
  • More than 86% of workload will be processed by cloud data centers

Content Delivery Networks (CDNs)

- Content is replicated over a set of data centers
- Users can connect to any replica (anycast)
  - Lower latency
  - More efficient network resource usage
  - Higher availability and accessibility
  - Inherently higher robustness
Robustness of CDNs

- CDNs are vulnerable to a wide range of physical-layer attacks aimed at service degradation
- **Link cut attacks**
  - Relatively low level of sophistication
  - Can cause outright service interruption
  - Efficiency of attacks is boosted by targeting the most critical links

A series of attacks on fiber network in San Francisco area
- Investigated by FBI
- $250,000 award offered by AT&T for information

By cutting only 2 links, the network is partitioned
Robustness of CDNs

• How to model the effects of link cut attacks in the anycast traffic scenarios?

• **Content accessibility**: the ability of a region in the network topology (e.g., a set of users connected to an aggregation node) to access a particular content that is replicated over a number of nodes
  • Depends on the replica placement and the link cut set

Degree centrality: determined by the nodal degree

No content accessibility for nodes C and D
Robustness of CDNs

• How to model the effects of link cut attacks in the anycast traffic scenarios?

• **Content accessibility**: the ability of a region in the network topology (e.g., a set of users connected to an aggregation node) to access a particular content that is replicated over a number of nodes
  • Depends on the replica placement and the link cut set

**Betweenness centrality:** equal to the number of shortest paths traversing the element

No content accessibility for nodes C and D
Robustness of CDNs

• How to model the effects of link cut attacks in the anycast traffic scenarios?

• **Content accessibility**: the ability of a region in the network topology (e.g., a set of users connected to an aggregation node) to access a particular content that is replicated over a number of nodes
  • Depends on the replica placement and the link cut set

**Closeness centrality:**
Based on the average distance to all other nodes

No content accessibility for nodes C and D
Robustness of CDNs

• How to model the effects of link cut attacks in the anycast traffic scenarios?

• **Content accessibility**: the ability of a region in the network topology (e.g., a set of users connected to an aggregation node) to access a particular content that is replicated over a number of nodes

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Clustering-based placement:
Nodes are clustered and the content is placed at the cluster centroids

All nodes can access content
Average 2 Terminal Reliability (A2TR)

- A well-known connectivity measure under link cuts from the literature
- Defined as the probability that a randomly chosen pair of nodes is connected\textsuperscript{[1,2]}. 
  \begin{align*}
  \text{A2TR} &= 1 \rightarrow \text{graph fully connected} \\
  \text{A2TR} &= 0 \rightarrow \text{graph completely disconnected}
  \end{align*}

- Parameters:
  - Graph G(V,E)
  - Set of subgraphs C

\[
A2TR = \frac{\sum |C_i| \times (|C_i| - 1)}{|V| \times (|V| - 1)}
\]

A2TR Example

- Fully connected network

\[
A2TR = \sum_{i=1}^{\left|C\right|} |C_i| \times (|C_i| - 1) = \frac{14 \times (14 - 1)}{14 \times (14 - 1)} = 1
\]
A2TR Example

- Completely disconnected network

\[ A2TR = \sum_{i=1}^{\mid C \mid} |C_i| \times (|C_i| - 1) \]

\[ = \frac{1 \times (1 - 1) + 1 \times (1 - 1) + \ldots + 1 \times (1 - 1)}{14 \times (14 - 1)} \]

\[ = \frac{0}{14 \times (14 - 1)} = 0 \]
A2TR Example

• A random cut

\[
A2TR = \frac{\sum_{i=1}^{\left|C\right|} |C_i| \times (|C_i| - 1)}{|V| \times (|V| - 1)} = \frac{6 \times (6 - 1) + 8 \times (8 - 1)}{14 \times (14 - 1)} = \frac{86}{182} = 0.4725
\]

• A randomly selected pair of nodes can be connected in 47% of cases
Content Accessibility in CDNs

- How to quantify the content accessibility on the example below?
- 2 replicas
- Best Case Scenario
- Worst Case Scenario
- Real Case Scenario
Average Content Accessibility (ACA)

- Measures the portion of nodes that are still able to connect to a replica for a given portion of cut links

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G(V,E)$</td>
<td>Network graph with nodes and links</td>
</tr>
<tr>
<td>$r$</td>
<td>Number of replicas</td>
</tr>
<tr>
<td>$C$</td>
<td>Set of connected components</td>
</tr>
<tr>
<td>$C_i$</td>
<td>A particular connected component with $</td>
</tr>
<tr>
<td>$x_i$</td>
<td>1 if there is a replica in connected component $C_i$, 0 otherwise</td>
</tr>
</tbody>
</table>

- **Best Case Scenario** – Replicas are spread across the largest connected components
- **Worst Case Scenario** – Replicas are confined in the smallest connected components
- **Real Case Scenario** – Replica placement is given
ACA in the Best Case Scenario (ACA-BCS)

- Content replicas are spread across the largest connected components
- Gives an upper bound on the ACA for a given number of replicas

\[ ACA_{bcs}(r) = \frac{\sum_{i=1}^{r} |C_i^{desc}|}{|V|} \]

\[
ACA_{bcs}(1) = \frac{\sum_{i=1}^{1} |C_i^{desc}|}{|V|} = \frac{6}{14} = 0.42
\]

\[
ACA_{bcs}(2) = \frac{\sum_{i=1}^{2} |C_i^{desc}|}{|V|} = \frac{6 + 5}{14} = 0.78
\]

\[
ACA_{bcs}(3) = \frac{\sum_{i=1}^{3} |C_i^{desc}|}{|V|} = \frac{6 + 5 + 3}{14} = 1
\]

\[ |V| = 14 ; |E| = 22 \]
ACA in the Worst Case Scenario (ACA-WCS)

- Gives a lower bound on ACA
- Replicas are confined in the smallest connected components

**Exact fit:**
- The replicas are confined in connected components whose size is equal to the number of replicas

**Best fit:**
- The replicas are located in connected components whose size is the closest to the number of replicas

```
Algorithm 1: Algorithm for the ACA_{wcs}

Data: G(V,E), r, C
Result: ACA_{wcs}(r)

for combination in binary 0..2^|C| − 1 do
    sum ← \(\sum_{i=1}^{|C|} |C_i| \times \text{combination}_i\);
    if sum = r then
        return \(\frac{\text{sum}}{|V|}\);
    end if
    5 \(\tilde{r} \leftarrow r\); CP ← C; sum ← 0;
while \(\tilde{r} > 0\) do
    if \(\exists i\) such that \(|CP_i| > \tilde{r}\) then
        \(C_{BF} \leftarrow \min_i(|CP_i| - \tilde{r})\);
        \(\tilde{r} \leftarrow \tilde{r} - |C_{BF}|\);
        sum ← sum + |C_{BF}|;
        CP ← CP \setminus C_{BF};
    else
        \(C_{BF} \leftarrow \min_i(\tilde{r} - |CP_i|)\);
        \(\tilde{r} \leftarrow \tilde{r} - |C_{BF}|\);
        sum ← sum + |C_{BF}|;
        CP ← CP \setminus C_{BF};
    end if
end while
return \(\frac{\text{sum}}{|V|}\);
```
ACA in the Worst Case Scenario (ACA-WCS)

\[ ACA_{wcs}(1) = \frac{3}{14} = 0.21 \]
\[ ACA_{wcs}(2) = \frac{3}{14} = 0.21 \]
\[ ACA_{wcs}(3) = \frac{3}{14} = 0.21 \]
\[ ACA_{wcs}(4) = \frac{5}{14} = 0.36 \]

\[ |V| = 14; |E| = 22 \]
ACA in the Real Case Scenario (ACA-RCS)

- Content replica placement is given beforehand

\[
ACA_{rcs}(r) = \frac{\sum_{i=1}^{\mid C \mid} |C_i| \times x_i}{|V|}
\]

\[
ACA_{rcs}(1) = \frac{\sum_{i=1}^{\mid C \mid} |C_i| \times x_i}{|V|} = \frac{5}{14} = 0.35
\]

\[
ACA_{rcs}(2) = \frac{\sum_{i=1}^{\mid C \mid} |C_i| \times x_i}{|V|} = \frac{5 + 3}{14} = 0.57
\]

\[
ACA_{rcs}(2) = \frac{\sum_{i=1}^{\mid C \mid} |C_i| \times x_i}{|V|} = \frac{5 + 3}{14} = 0.57
\]

\[
|V| = 14 \ ; \ |E| = 22
\]
Simulation setup

- Scenarios:
  - 3 network topologies\(^{[1]}\)
  - Replica placement strategies:
    - Degree centrality
    - Betweenness centrality
    - Closeness centrality
    - Clustering with K-Means
  - Simultaneous and sequential link cut attacks
    - Based on link betweenness

<table>
<thead>
<tr>
<th>Topology</th>
<th>n</th>
<th>m</th>
<th>k ± σ</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprint</td>
<td>11</td>
<td>18</td>
<td>3.27±1.42</td>
<td>4</td>
</tr>
<tr>
<td>Géant</td>
<td>40</td>
<td>61</td>
<td>3.05±1.92</td>
<td>8</td>
</tr>
<tr>
<td>Garr</td>
<td>61</td>
<td>75</td>
<td>2.45±2.58</td>
<td>8</td>
</tr>
</tbody>
</table>

Discrepancies between A2TR and ACA

- Sprint network (11 nodes, 18 links)

A2TR is not able to capture the connectivity of CDNs
ACA-BCS vs. ACA-WCS

- Sprint network (11 nodes, 18 links)

Difference from the best to the worst case scenario

Difference due to the number of replicas
Impact of the number of replicas

- How does the increase in the number of replicas change ACA?
Impact of the replica placement on ACA-RCS

- Géant network (40 nodes, 61 links, 2 replicas)
Impact of the replica placement on ACA-RCS

Sprint

Garr
Impact of the type of attack on ACA

- Sprint network (11 nodes, 18 links, 2 replicas)
- Simultaneous cuts: link criticality evaluated once
- Sequential cuts: link criticality re-evaluated in the modified topology upon each cut

![Diagram showing the impact of type of attack on ACA](image-url)
Impact of the type of attack on ACA

Géant

Garr
Conclusions and next steps

• State-of-the-art (A2TR) strategies are not applicable to gauge CDN robustness to link cuts
• The proposed Average Content Accessibility (ACA) measure can capture CDN robustness in the worst, the best and realistic case
• Adding replicas does not always significantly increase content accessibility
• Content placement strategies greatly impact content accessibility
• Simultaneous and sequential attacks (link cuts) affect the content accessibility in different ways
• Next steps:
  • Consider the impact of link cuts to other parameters, e.g., latency and network resource usage
  • Analyze/propose content placement strategies considering content accessibility
  • Find the right number of replicas to support a required robustness level
  • Develop network topology update/enhancement approaches to improve content accessibility in CDNs
Questions?

Thank you for your attention!

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