Fault-Tolerant Virtual Network Mapping to Provide Content Connectivity in Optical Networks

M. Farhan Habib\(^1\), Massimo Tornatore\(^2\), Biswanath Mukherjee\(^1\)

\(^1\)Department of Computer Science, University of California Davis
\(^2\)Dipartimento di Elettronica e Informazione, Politecnico di Milano
mfhabib@ucdavis.edu, tornator@elet.polimi.it, mukherje@cs.ucdavis.edu

Abstract: We define content connectivity as the reachability of every content from any point of an optical network. We propose a scheme for virtual network mapping and content placement to ensure content connectivity after failures.

© 2012 Optical Society of America

OCIS codes: 060.4257, 060.4261, 060.4256.

1. Introduction

In today’s optical network, more than 90% of the total Internet traffic is generated due to content dissemination [1]. The Internet has evolved from an end-to-end communication medium into a content sharing and distribution medium. Popularity of Internet services (e.g., data in cloud) has increased rapidly over the decades, stimulated by new content-hungry broadband applications on end-user devices (e.g., smart phones), such as distributed storage, collaborative applications, and multimedia streaming, to name a few. A recent study shows that real-time entertainment services (e.g., Netflix, Youtube, etc.) account for 60% of peak downstream traffic in North America [2]. In a content provider network (datacenter network such as Google’s or content delivery network such as Akamai’s), contents/services are replicated over multiple storage locations (e.g., servers), such that a user request can be served from any of the locations that hosts the specific content (this concept is called anycasting).

The Internet was originally designed to provide end-to-end communication that can survive failures. Thus, network connectivity (i.e., reachability of every network node from all other nodes) has always been a primary metric to measure the survivability of a network against failures. In a disconnected network, a disrupted end-to-end connection cannot be recovered if the two end nodes of the connection fall in two disconnected components. Recently, due to increasing threat of large-scale natural disasters (e.g., earthquake) and intentional attacks (e.g., attacks using weapons of mass destruction) on communication networks, survivability of connectivity against large failures has become a major concern. For example, the December, 2006 earthquake in Taiwan cut fibers connecting Asia and North America, reducing the Internet access capacity of Hong Kong and China by 100% and 74%, respectively [3].

As network is becoming increasingly end-to-content (rather than end-to-end) connection provider, we ask the question "Is it worth to provide protection for network connectivity?" It might be the case that a failure disconnects the network, but if a content is replicated in all disconnected portions of the network, the required service can still be provided. We define content connectivity as the reachability of every content from any point of a network. Note that content connectivity provides less protection than network connectivity in terms of end-to-end connectivity. As all we need to maintain is reachability of contents, we note that network connectivity is required during regular operation, but after a failure, we need to ensure content connectivity until the network connectivity is recovered. Different failures may create different sets of disconnected components. Thus, the problem of ensuring content connectivity is non-trivial. A content provider network is generally an overlay network (i.e., virtual/logical network) mapped over a physical (i.e., optical backbone) network. Virtual network mapping is defined as the assignment of virtual network resources to the elements of physical network, e.g., virtual links are created using optical layer lightpaths. In this study, we formalize and investigate the new problem of virtual network mapping to provide content connectivity in optical networks. We present an integrated Integer Linear Program (ILP) formulation for mapping virtual network over physical network and content placement such that content connectivity is ensured after failures. We show that maintaining content connectivity instead of network connectivity has two major benefits:

- Maintaining network connectivity may not always be possible after failures (e.g., 2006 Taiwan earthquake). Content connectivity can help us to provide/continue services in such scenarios.
- Ensuring content connectivity requires less network resources than network connectivity.

2. Survivable Mapping

Maintaining content connectivity requires efficient content placement exploiting the a-priori knowledge of potential vulnerable locations in the network. The success of providing failure-resilient content connectivity depends on virtual network mapping as a single failure in the physical network may cause multiple failures in the overlay network which might make it disconnected [4]. Below, we explain the concept of survivable mapping that ensures connectivity after failure.
Given
• \( G(V, E) \): Physical topology; \( V \) is the set of nodes and \( E \) is the set of directed links
• \( G_L(V_L, E_L) \): Logical topology; \( V_L \subset V \) and \( E_L \subset E \)
• \( V' \subset V_L \): Set of storage locations; \( C \): Set of contents
• \( W \): Physical link capacity; \( Z \): Set of SRGs
• \( K \): Maximum number of replicas per content

Output
• Logical topology mapping
• Replica locations of each content

Objective
\[ \min \left( \sum_{i,j} \sum_{s,t} f_{ij} \right) : \text{Minimize total wavelength usage} \]

Variables
• \( f_{ij} \in \{0,1\} : (s,t) \in V_L \text{ goes through } (i,j) \in V \)
• \( C^u_{z} \in \{0,1\} : z \in Z \text{ disrupts } (s,t) \in V_L \)
• \( P^u_{st} \in \{0,1\} : \text{Node } s' \text{ can reach content } c \text{ using logical link } (s,t) \text{ after failure of SRG } z \)
• \( A^u_{st} \in \{0,1\} : \text{Node } s' \in V_L \text{ can reach content } c \text{ located at } s \in V \)
• \( R^{(c,s)} \in \{0,1\} : \text{Content } c \in C \text{ is replicated at storage location } s \in V' \)

Constraints

Content placement
\[ \sum_{s,t} R^{(c,s)} \leq K \quad \forall s \in V', \forall c \in C \]  \hspace{1cm} (1)
\[ A^u_{st} \leq R^{(c,s)} \quad \forall s' \in V_L, \forall c \in C, \forall s \in V \]  \hspace{1cm} (2)

Physical-layer-flow to route logical links
\[ \sum_{j:(i,j) \in E} f_{ij}^{(s,t)} - \sum_{j:(j,i) \in E} f_{ji}^{(s,t)} = \begin{cases} 1 & \text{if } i = s \\ -1 & \text{if } i = t \\ 0 & \text{otherwise} \end{cases} \forall (s,t) \in E_L, \forall (i,j) \in E \]  \hspace{1cm} (3)

Logical-layer-flow to ensure content-connectivity
\[ \sum_{(i,j) \in z} f_{ij}^{(s,t)} / M \leq C^u_{z} \leq \sum_{(i,j) \in z} f_{ij}^{(s,t)} \forall (s,t), \forall (i,j), \forall z \]  \hspace{1cm} (4)
\[ P^u_{st} \leq 1 - C^u_{z} \quad \forall s', \forall c, \forall (s,t), \forall z \]  \hspace{1cm} (5)

3. Problem Formulation

Below, we present an Integer Linear Program (ILP) formulation which models and solves a) mapping of logical (i.e., virtual) network over physical network and b) content placement. The objective is to ensure content connectivity after failures (represented as Shared Risk Groups, SRGs) while minimizing resource usage. To simplify the model, we assume that servers have unlimited storage capacity (but generalization of this constraint is part of our ongoing research).
Constraint 1 restricts the number of replicas per content. Constraint 2 ensures that a node (i.e., storage location) can only be used to serve a request if it hosts the requested content. Constraint 3 maps the logical links into optical layer lightpaths. Constraint 4 defines $C^w_c$. Constraint 5 ensures that logical link $(s \rightarrow t)$ can be used to satisfy a request after SRG $z$ occurs only if $s \rightarrow t$ survives the failure. Constraint 6 ensures that at least a replica of each content is reachable from every node after a failure.

### 4. Illustrative Numerical Examples

#### Table 1: Wavelength usage for different number of SRGs.

<table>
<thead>
<tr>
<th>Scenario</th>
<th># SRGs = 0</th>
<th># SRGs = 1</th>
<th># SRGs = 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content Connectivity</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Network Connectivity</td>
<td>17</td>
<td>18</td>
<td>-</td>
</tr>
</tbody>
</table>

In Fig. 3, we show a 14-node physical topology (NSF Net) and a 6-node virtual topology to be mapped over it. Nodes 7 and 10 have storage capacity and we consider a single content in the network. We consider all single physical link failures and one SRG (links 5-7 and 1-8) which is critical for the connectivity of the logical network. Using the ILP, we found that maintaining content connectivity takes 15 wavelengths whereas maintaining network connectivity takes 18 wavelengths (20% more even with these small SRGs). Figure 4 shows the effect of number of replicas on network resource usage. Here we use the same physical and logical topology and SRGs as in Fig. 3, but assume that every node in the logical network has storage capacity. We see that, with a small increase in number of replicas, wavelength usage drops significantly. But, eventually the wavelength usage converges to a certain value. For the same physical and logical topology as in Fig. 3, we also studied the effect of number of storage locations on network resource usage considering one content and two replicas ($k = 2$) of the content. We found that, for single storage location, number of wavelengths used is 18. For any other number of storage locations (note that we cannot have more than two replicas), the wavelength usage is 15. As number of replicas is fixed, additional storage locations do not reduce resource consumption.

Table 1 shows the effect of SRG on connectivity. Here we consider three scenarios. All of the three scenarios consider all single physical link failures. In addition, scenario 2 considers SRG 1 (links 5-7 and 1-8), and scenario 3 considers SRG 1 and SRG 2 (links 6-10, 6-14). We see that, in all three scenarios, wavelength usage to maintain content connectivity is the same. For network connectivity, wavelength usage in scenario 2 is greater than in scenario 1. For scenario 3, there is no survivable mapping to maintain network connectivity. This result indicates that the higher the number of SRGs, the higher the benefit of providing content connectivity rather than network connectivity. The proposed model can be used to study the effects of different parameters on virtual network mapping and to compare different aspects of content connectivity and network connectivity.

#### 5. Conclusion

We defined content connectivity and proposed a scheme to maintain content connectivity after failures in optical networks. We showed that content connectivity can provide/continue content/services after failures even when network connectivity cannot be maintained. We also showed that content connectivity provides the required protection of content/services with fewer resource consumption than network connectivity. We studied the effects of number of SRGs and content replicas on resource usage.

### References