OPTICAL NETWORKS

Traffic Grooming

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2005
Introduction

- A lightpath is a wavelength circuit, which may span multiple fiber links and be routed by the intermediate optical switches between a given node pair.
- The bandwidth of a lightpath in an optical WDM backbone network is quite high (10 Gbps (OC-192) today, and expected to grow to 40 Gbps (OC-768) soon).
- Only a fraction of the customers are expected to have a need for such a high bandwidth.
- Many will be content with a lower bandwidth, e.g., STS-1 (51.84 Mbps), OC-3, OC-12, OC-48, for backbone applications.
- High-bandwidth wavelength channels will be filled up by many low-speed traffic streams.
- Efficiently provisioning customer connections with such diverse bandwidth needs is a very important problem.

⇒ the traffic-grooming problem.
Problem Statement

The traffic-grooming problem:

- **Given:**
  - A network configuration (physical topology, number of transceivers at each node, number of wavelengths on each fiber, and the capacity of each wavelength)
  - A set of connection requests with different bandwidth granularities, such as OC-12, OC-48.

- **Determine:**
  - how to set up lightpaths to satisfy the connection requests.

Because of the sub-wavelength granularity of the connection requests, one or more connections can be multiplexed on the same lightpath.
Problem Statement

- The set of connection requests can:
  - all be given in advance: static traffic
  - or given one at a time: dynamic traffic.
- Traffic grooming with static traffic:
  - In a non-blocking scenario:
    - the network has enough resources to carry all of the connection requests,
    - the objective is to minimize the network cost, e.g., total number of wavelength links used, while satisfying all the requests.
  - In a blocking scenario:
    - not all connections can be set up due to resource limitations,
    - the objective is to maximize the network throughput.
- Traffic grooming with dynamic traffic:
  - connections arrive one at a time,
  - the objective is to minimize the network resources used for each request, which implicitly attempts to minimize the blocking probability for future requests.
Sub-problems

Traffic grooming is usually divided into four sub-problems: (not necessarily independent)

- Determining the virtual topology that consists of lightpaths,
- Routing the lightpaths over the physical topology,
- Performing wavelength assignment to the lightpaths,
- Routing the traffic on the virtual topology.

- The virtual-topology design problem is conjectured to be NP-hard.
- In addition, routing and wavelength assignment (RWA) is also NP-hard.
- Therefore, traffic grooming in a mesh network is also a NP-hard problem.
Solving the Problem

- To solve the static traffic-grooming problem, one approach is to deal with the four sub-problems separately.
  - First determines the virtual topology,
  - then perform routing and wavelength assignment,
  - finally routes the traffic requests.
- There are considerable research results on each sub-problem already and they can be utilized to solve the traffic-grooming problem.
- This divide-and-conquer method makes traffic grooming easier to handle.
- But it cannot achieve the optimal solution even if we can get the optimal solution for each sub-problem.
- The solution to one sub-problem might affect how optimally another sub-problem can be solved.
Solving the Problem

- Another approach is to solve the four sub-problems as a whole.
- This approach has a potential to achieve better performance.
  - It can take into account all the constraints regarding the four sub-problems simultaneously.
- With static traffic, the traffic-grooming problem can be formulated as an integer linear program (ILP).
  - An optimal solution can be obtained for some relatively small networks.
  - However, an ILP is not scalable and cannot be directly applied to large networks.
- One way to make the problem tractable is to develop heuristic algorithms to jointly solve the grooming problem for one connection request at a time.
Research on Traffic Grooming

Traffic grooming is an important and practical problem for designing WDM networks and it is receiving increasing research attention both in academia and in industry.

Static Traffic Grooming

- The bandwidth of connection requests can be some fraction of the lightpath capacity.
- For the static traffic-grooming problem, a set of connection demands are given, and they need to be established on the network.
- Example:
  - Each fiber has two wavelength channels.
  - The capacity of each wavelength channel is OC-48, i.e., approximately 2.5 Gbps.
  - Each node is equipped with a tunable transmitter and a tunable receiver.
Example

- There are three connection requests:
  - (0, 2) with bandwidth requirement OC-12,
  - (2, 4) with bandwidth requirement OC-12,
  - (0, 4) with bandwidth requirement OC-3.
- Two lightpaths have already been set up to carry these connections.
Example

- The resources at nodes 0 and 4 are busy:
  - transmitter in node 0
  - receiver in node 4
- We cannot set up a lightpath from node 0 to node 4.
- Connection 3 has to be carried by the spare capacity of the two existing lightpaths.
Grooming Techniques

- Different connection requests between the same node pair \((s, d)\) can be either:
  - groomed on the same lightpath which directly joins \((s, d)\),
  - or routed separately through different virtual paths.
- A connection may traverse multiple lightpaths if no resources are available to set up a lightpath between the source and the destination directly.
- The node architecture should support traffic grooming to allow such multiplexing over lightpaths.
Node Architecture

- Low-speed connection requests will be multiplexed on the same lightpath channel by using an electronic-domain TDM-based multiplexing technique.
- The node architecture is composed of two components:
  - WRS
  - Access station.
- WRS performs wavelength routing and wavelength multiplexing/de-multiplexing.
  - It is composed of an OXC, Network Control and Management Unit (NC&M), and Optical Multiplexer/De-multiplexer.
  - In the NC&M unit, the network-to-network interface (NNI) will configure the OXC and exchange control messages with peer nodes on a dedicated wavelength channel (wavelength 0).
  - The network-to-user interface (NUI) will communicate with the NNI and exchange control information with the user-to-network interface (UNI), the control component of the access station.
Node Architecture

- The access station performs local traffic adding/dropping and low-speed traffic-grooming functionalities.
  - Each access station is equipped with some transmitters and receivers.
  - Multiplexing low-speed connections to high-capacity lightpaths is done by the MPLS/IP router using a software-based queuing scheme.
Types of OXC

- Depending on their architectures and technologies employed, different OXCs may have different multiplexing and switching capabilities.
- This results in different capabilities for grooming low-speed traffic streams onto high-capacity wavelength channels.
- There are four types of OXC in terms of grooming capabilities.
  - Non-grooming
  - Single-hop grooming
  - Multi-hop partial-grooming
  - Multi-hop full-grooming
Non-grooming OXC

- This type of OXC can be built with either transparent or opaque approach.
- It has wavelength-switching capability.
- If the transparent approach is used, it is possible for this type of OXC to switch at higher bandwidth granularity, such as waveband (a group of wavelengths) or fiber.
- There is no low-data-rate port.
- Thus, extra aggregation/de-aggregation network elements are needed to work with this type of OXC if low-speed traffic streams need to be supported.
Single-hop Grooming OXC

- Will only switch traffic at wavelength granularity.
- It may have some lower-data-rate ports, which can directly support low-speed traffic streams.
- The traffic from these low-speed ports can be multiplexed onto a wavelength channel using a TDM scheme, before the traffic enters the switch fabric.
- Does not have the capability to switch low-speed streams at intermediate nodes.
- All of the low-speed streams on one wavelength channel at the source node will be switched to the same destination node.
Multi-hop Partial-grooming OXC

- The switch fabric is composed of two parts:
  - a wavelength-switch fabric (W-Fabric),
  - an electronic-switch fabric which can switch low-speed traffic streams. The electronic-switch fabric is also called grooming fabric (G-Fabric).
- With this hierarchical switching and multiplexing architecture, it can:
  - switch low-speed traffic streams from one lightpath to another
  - groom them with other low-speed streams without using any extra network element.
- Assuming that the lightpath capacity is OC-N and the lowest input port speed of the electronic switch fabric is OC-M ($N \geq M$): the ratio between $N$ and $M$ is called the **grooming ratio**.
- Only a few of wavelength channels can be switched to the G-Fabric for switching at finer granularity.
- The number of ports, which connect the W-Fabric and G-Fabric, determines how much multi-hop grooming capability this OXC has.
Multi-hop Partial-grooming OXC
Multi-hop Full-grooming OXC

- It can provide full grooming functionality.
- For every OC-N wavelength channel arriving at the OXC:
  - It will be de-multiplexed into its constituent OC-M streams before it enters the switch fabric,
  - These OC-M traffic streams will be switched in a non-blocking manner.
  - Then, the switched streams will be multiplexed back onto different wavelength channels.
- An OXC with full-grooming functionality has to be built using the opaque approach.
- The switching fabric can be viewed as a large grooming fabric.
Heuristic Approach

- The optimization problem of traffic-grooming is $NP$-complete.
- A heuristic approach to solve the problem: Maximizing single-hop traffic (MST).
  - $T(s,d)$ denote the aggregate traffic between node pair $s$ and $d$, which has not been successfully carried.
  - $t(s, d)$ denote one connection request between $s$ and $d$, which has not been successfully carried yet.
  - $C$ denote the wavelength capacity.
MST Algorithm

- This heuristic attempts to establish lightpaths between source-destination pairs with the highest $T(s, d)$ values, subject to:
  - constraints on the number of transceivers at the two end nodes,
  - the availability of a wavelength in the path connecting the two end nodes.
- The connection requests between $s$ and $d$ will be carried on the new established lightpath as much as possible.
- If there is enough capacity in the network, every connection will traverse a single lightpath hop.
- If there are not enough resources to establish enough lightpaths, the algorithm will try to carry the blocked connection requests using currently available spare capacity of the virtual topology.
MST Algorithm

1. Construct virtual topology:
   (a) Sort all of the node pairs \((s, d)\) according to the sum of uncarried traffic request \(T(s, d)\) between \((s, d)\) and put them into a list \(L\) in descending order.
   (b) Try to setup a lightpath between the first node pair \((s, d)\) in \(L\) using first-fit wavelength assignment and shortest-path routing, subject to the wavelength and transceiver constraints.
      - If it fails, delete \((s, d)\) from \(L\);
      - otherwise, let \(T(s, d) = \text{Max}[ T(s, d) - C, 0] \) and go to Step 1a until \(L\) is empty.

2. Route the low-speed connections on the virtual topology constructed in Step 1.
   (a) Satisfy all of the connection requests which can be carried through a single lightpath hop, and update the virtual topology network state.
   (b) Route the remaining connection requests based on the current virtual topology network state, in the descending order of the connections’ bandwidth requirement.
Results

- Throughput results comparison between ILP and heuristic algorithms (total traffic demand is OC-988).
- 6-node network
- The two proposed algorithms are relatively simple.
- Using other RWA algorithms instead of adaptive routing and first-fit wavelength assignment, it may be possible to develop other complex heuristic algorithms to achieve better performance.

<table>
<thead>
<tr>
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<th>Multi-hop (ILP)</th>
<th>Single-hop (ILP)</th>
<th>Heuristic (MST)</th>
<th>Heuristic (MRU)</th>
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<tbody>
<tr>
<td>T=3, W=3</td>
<td>74.7% (OC-738)</td>
<td>68.0% (OC-672)</td>
<td>71.0% (OC-701)</td>
<td>67.4% (OC-666)</td>
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<td>T=4, W=3</td>
<td>93.8% (OC-927)</td>
<td>84.1% (OC-831)</td>
<td>89.4% (OC-883)</td>
<td>93.6% (OC-925)</td>
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<td>97.9% (OC-967)</td>
<td>85.7% (OC-847)</td>
<td>94.4% (OC-933)</td>
<td>94.4% (OC-933)</td>
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<tr>
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<td>85.7% (OC-847)</td>
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<td>94.4% (OC-933)</td>
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<tr>
<td>T=3, W=4</td>
<td>74.7% (OC-738)</td>
<td>68.0% (OC-672)</td>
<td>71.0% (OC-701)</td>
<td>67.4% (OC-666)</td>
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<td>84.7% (OC-837)</td>
<td>93.1% (OC-920)</td>
<td>93.6% (OC-925)</td>
</tr>
<tr>
<td>T=5, W=4</td>
<td>100% (OC-988)</td>
<td>95.5% (OC-944)</td>
<td>100% (OC-988)</td>
<td>100% (OC-988)</td>
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