Grooming Telecommunications Networks

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Abstract

The challenge of creating cost-effective and efficient designs for telecommunications networks is often complicated by conflicts in the "low-level" activities of circuit routing and channel assignment. Grooming techniques—conversions of signals between distinct transmission channels—can address such conflicts and substantially enhance the effective capacity of a given transport system. This paper provides an overview of, and introduction to, this neglected, yet important area of research

Although grooming has been an issue in telecommunications network design since the invention of multiplexing, many are unfamiliar with the term and the topic has received scant attention from the research community. It is the goal of this article to introduce network grooming to the reader and demonstrate its importance; it is the objective of this special issue of *ONM* to provide fresh theory and empirical evidence of the impact of grooming on optical network designs.

Grooming is an industry term used to describe the optimization of capacity utilization in transport systems by means of cross-connections or conversions between different transport systems or layers within the same system. Grooming typically involves the use of frequency or time-slot conversion equipment to increase the effective capacity and efficiency of a network.

1 Multiplexing and Bundling

The motivation for grooming springs from the application of *multiplexing* and *bundling*, techniques that combine multiple traffic streams into composite, higher-speed transport units (Doverspike, 1991). Multiplexing is the simultaneous transmission of different messages over the communication network through a partitioning of the available bandwidth or other resource.

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Optical networks make use of three types of multiplexing, each of which can be viewed as partitioning a given resource into a set of separate resources (Stern & Bala, 1999):

- *Space-division multiplexing* (SDM)—the partitioning of physical space to increase transport bandwidth. For example, bundling a set of fibers into a single cable or using several cables within a given network link
- *Frequency-division multiplexing*(FDM)—partitioning the available frequency spectrum into a set of independent channels. The use of FDM within optical networks is termed (dense) wavelength-division multiplexing (DWDM or WDM) which enables a given fiber to carry traffic on many distinct wavelengths (λ-channels). WDM divides the optical spectrum is into coarser units, called wavebands, which are further divided into λ-channels.
- *Time-division multiplexing* (TDM)—dividing the bandwidth's time domain into repeated, fixed-length time-slots. Using TDM, multiple signals can share a given wavelength if they are non-overlapping in time.

Clearly, a given optical network can use all three multiplexing and bundling techniques to transport traffic. From a top-down, de-multiplexing, and partitioning viewpoint, network links consist of cables of bundled fibers, each fiber uses WDM to carry multiple wavelengths, each with several wavebands made up of multiple λ-channels; the λ-channels may carry many separate signals through the application of TDM. From a bottom-up, multiplexing point of view, separate signals can be combined via TDM to create λ-channels that are grouped into wavebands, each of which is transported via one of many WDM wavelengths in a fiber; fibers are bundled into cables, and each network link can represent multiple cables.

The motivation for multiplexing is simple. Most messages take only a fraction of the bandwidth available. By multiplexing the communications network, multiple smaller messages can be sent simultaneously over the same transmission medium, often in opposite directions, thus increasing the capacity utilization and driving down the cost per message transmitted.

2 Routing and Channel Assignment for Lightpaths

Point-to-point, origin-destination connections (ODs) are routed over optical networks via lightpaths, logical circuits transported from origin node to destination node via one or more fiber links. In wavelength-routed networks without conversion equipment, lightpaths are established by assigning a distinct channel (e.g., wavelength) to the circuit and ensuring continuity of the channel from

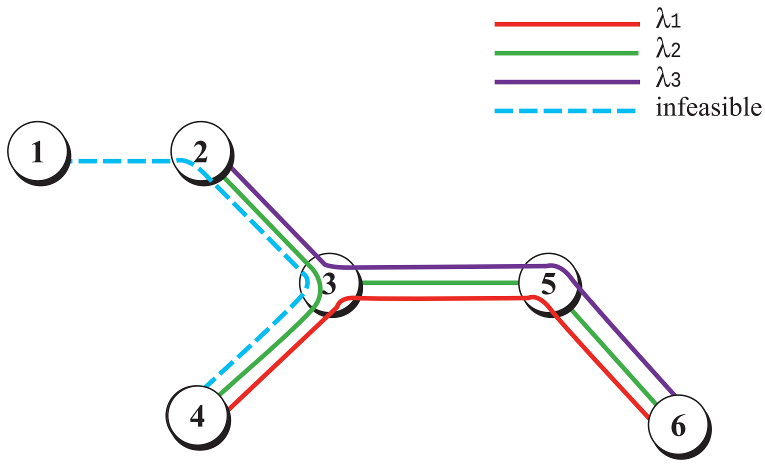

Figure 1: Unroutable 1-4 traffic due to wavelength-continuity constraints

source to destination. These wavelength-continuity and distinct-channel assignment (DCA) constraints require that the connection be carried on the same wavelength on all links in the lightpath. Similar constraints apply to other bandwidth-partitions in FDM networks, time-slots in TDM designs, and λ-channels in waveband-routed networks.

Lightpath routing and channel-assignment (RCA) for all ODs in a given network can be a computationally challenging problem (Day & Ester, 1997; Mukherjee, 1997) because of the wavelength-continuity and DCA constraints. Moreover, these two rules of operation can lead to channel conflicts and contention, even with optimized designs. These conflicts can result in stranded, unused, and unusable capacity (both working and spare) and limitations on wavelength reuse. It is the goal of grooming to minimize such inefficiencies.

The hypothetical optical network model shown in Figure 1 illustrates the potential impact of the wavelength continuity and DCA constraints (Betts, 1998). Each span has an identical capacity of 3λ and there is a demand of 1λ between the following origin- destination node pairs: 1,4, 2-4, 4-6, 3-5, 6-5, and 2-6.

Within the tree topology, the routing for each demand is unique and there is sufficient aggregate capacity on the spans to accommodate all O-D circuits. However, not all of the demands can be assigned to one of the three λ-channels available on each link. O-D 1-4 cannot be accommodated; hence the routing and channel-assignment problem—and the overall design—is infeasible. One solution is to add one additional λ of capacity on links (1,2), (2,3), and (3,4) to accommodate this circuit, giving an overall capacity utilization of $13/18 = 72.2\%$.

3 Grooming Solutions

Whether the technology is electrical, optical, radio, or microwave, grooming involves the switching of messages from one channel, frequency, time-slot, wavelength, color, λ-channel, waveband, or fiber cable to another. Grooming devices include: wavelength converters; cross-connects, both optical and electrical (Jackman et al., 1999); time-slot interchange (TSI) equipment (Carpenter, et al); and signal regenerators, which can perform wavelength interchange as a byproduct of the regeneration process.

Grooming of telecommunications networks includes traffic optimization with multiple transport systems, such as SONET and WDM, with the necessary cross- connection switching and bundling issues (Carpenter et al., 1997; Lardies et al., 2001). Grooming also includes optimization of traffic over multiple layers of a single transportation system such as WDM (Gurucharan et al., 2001; Thiagarajan & Somani, 2001), and DWDM (Cox & Sanchez, 2001).

Grooming includes both the routing and bundling of traffic and the topological design of the networks themselves. The key component for a problem to be defined as a grooming problem is the movement of traffic from one channel, time-slot, layer, transport system, etc., through a switch or cross-connection point to another.[1]

How can the inclusion of grooming facilities help? Good grooming can improve network efficiency by:

- Permitting a given lightpath to follow different ?-channels or wavelengths and other transport circuits to change channel and time-slot assignments their O-D paths;
- Eliminating the wavelength-continuity and distinct-channel assignment constraints on some or all circuits;
- Reducing the capacity that is wasted by low-level channel-assignment conflicts, thereby the need for additional bandwidth (Lardies et al., 2001);
- Mathematically increasing the number of routing possibilities; and
- Decomposing a large RCA problem into a series of smaller, simpler ones.

The effectiveness of grooming can be illustrated by applying it to the hypothetical network problem described above. If, instead of adding capacity on three spans, wavelength conversion is enabled at node 3, all demands can be routing on existing wavelengths (see Figure 2).

[1] From this point of view, traffic grooming exists not only in telecommunication networks, but also in any transportation network such as highway systems, water distribution systems, electricity distribution systems, logistical supply systems, etc. We will limit our discussion to grooming issues within telecommunication networks.

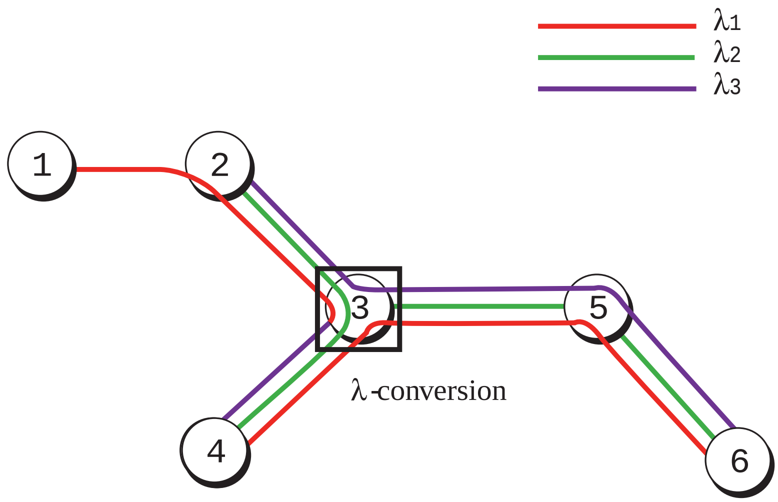

Figure 2: RCA feasibility achieved through λ-conversion at node 3 (Betts, 1998)

The grooming equipment eliminates lightpath 1-4's color clash with demand 4-6 on link (3,4) by switching the connection's wavelength from λ_2 to λ_1 at node 3. This increases the usable capacity of the network, permits λ_2 to be used and re-used on every network link, avoids the need for a fourth wavelength on three spans, and results in a 13/15 or 86.7% capacity utilization (an efficiency increase of 14.5%).

Cost figures are needed to evaluate whether the tradeoff between the additional grooming-equipment cost and the added-wavelengths cost is truly worthwhile. The grooming of electrical networks is commonplace and the cost savings, especially in large systems, can be substantial. Optical groomers involve complex and (currently) expensive photonic technology, and design optimization involving the economic tradeoffs is critical to making the business case.

Another well-known problem set that falls within the grooming genre is the concentration of multiple messages from multiple sources into a single large bundle which are then sent over high capacity transmission media, and the de-concentration and delivery of these messages to their intended destination (Doverspike, 1991). The location of concentrators and the routing of messages throughout a network with concentrators continues to a significant issue to groomers. However, the act of concentration and de-concentration is usually referred to as bundling, and the concentration device will be a digital cross-connect (DXC), an Optical to Electrical to Optical (O-E-O) switch, or something similar.

As before, grooming reduces the capacity that is wasted by low-level channel-assignment conflicts, and thus reduces the need for additional bandwidth (Lardies et al., 2001). As can be seen from the above examples, a few of the traditional problem domain areas that impact grooming include stochastic and deterministic routing, topological network design and network capacity design.

4 Grooming Models

Grooming decision problems can usually be represented as mixed-integer linear-programming and graph problems, are typically NP-complete, and must be solved with heuristic techniques for instances of any significant size (Chu & Modiano, 1998; Gerstel & Ramaswami, 2000). In the past, practitioners have typically dealt with these problems by partitioning the problem into sub-problems that can be more readily solved. The partitioning point is typically at the switching (or cross connection) point. When these problems are not dealt with holistically, the solution is almost always sub-optimal. However, these problems tend to be so complex that the only realistic way to solve them has been to consider the sub-problems separately. Recent advances in the areas of solution techniques, commercial software, and computer processing capabilities enable us to grapple with these extremely large and difficult problems in a holistic manner (Cosares et al., 1995; Reingold, 1999).

While the basic problems and concepts of grooming telecommunications networks are well-defined, the underlying combinatorial problems are computationally daunting. Effective algorithms and realistic models are starting to emerge; yet many high-impact problems remain unexplored. It is hoped that this introduction and review of the area will encourage readers to explore these advances and, perhaps, take up the challenge of creating networks that are, if not necessarily polite and attractive, at least well-groomed.

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