Computer Networks 69 (2014) 147–156

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Survey Paper

Hierarchical traffic grooming: A tutorial

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ARTICLE INFO

Article history:
Received 23 September 2013
Received in revised form 21 April 2014
Accepted 22 April 2014
Available online 14 May 2014

Keywords:
Traffic grooming
Hierarchical grooming
Network design

ABSTRACT

Traffic grooming is concerned with the design, operation, and control of networks with multigranular bandwidth demands. As the number of resources in a multigranular network increases rapidly with the network size, wavelength capacity, and load, a scalable framework for managing these entities becomes essential. Hierarchical traffic grooming facilitates the control and management of multigranular WDM networks. In this paper, we present a survey of traffic grooming schemes for optical networks that make use of architectures, algorithms and design techniques that impose a hierarchical structure on the network topology.

1. Introduction

Traffic grooming is the field of study that is concerned with the development of algorithms and protocols for the design, operation, and control of networks with multigranular bandwidth demands [1]. As the number of logical entities (including sub-wavelength channels, wavelengths, wavebands, and fibers) that need to be controlled in a multigranular network increases rapidly with the network size, wavelength capacity, and load, a scalable framework for managing these entities becomes essential for future wide area WDM networks.

Several variants of the traffic grooming problem have been studied in the literature under a range of assumptions regarding the network topology, the nature of traffic, and the optical and electronic switching model [2–10]. Typically, an integer linear programming (ILP) formulation serves as the basis for reasoning about and tackling the problem. One crucial concern about such formulations is that they are solvable only for small network topologies [11]. For larger topologies representative of commercial networks, the ILP formulation cannot be solved to optimality within a reasonably amount of time (for instance, within a few hours). Therefore, the offline traffic grooming problem has mostly been addressed using heuristic algorithms [12] whose quality cannot be easily characterized. Other approaches tackle the problem by manipulating the ILP formulation using decomposition or column generation techniques [13].

Most of the above studies regard the network as a flat entity for the purposes of lightpath routing, wavelength assignment, and traffic grooming. It is well-known, however, that in existing networks resources are typically managed and controlled in a hierarchical manner. The levels of the hierarchy either reflect the underlying organizational structure of the network or are designed in order to ensure scalability of the control and management functions. Accordingly, several studies have adopted a variety of hierarchical approaches to traffic grooming that, by virtue

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http://dx.doi.org/10.1016/j.comnet.2014.04.019
1389-1286/

of decomposing the network, scale well and are more compatible with the manner in which networks operate in practice.

In this paper, we present a survey of traffic grooming schemes for optical networks that make use of architectures, algorithms and design techniques that impose a hierarchical structure on the network topology. In Section 2, we examine early research in hierarchical traffic grooming for networks with symmetric or acyclic topologies, including rings, torus, trees, and stars. In Section 3, we review a general framework for hierarchical grooming in networks of general topology, that decomposes the problem into three logical subproblems: clustering, hierarchical virtual topology and traffic routing (H-VTTR), and routing and wavelength assignment (RWA). In Section 4, we discuss and compare several variants of the H-VTTR subproblem. We conclude the survey in Section 5.

2. Hierarchical grooming in elemental topologies

2.1. Ring networks

Early research in traffic grooming focused on ring topologies [2–4], mainly due to the practical importance of upgrading the existing SONET/SDH infrastructure to support multiple wavelengths. A point-to-point WDM ring is a straightforward extension of a SONET/SDH network, but requires that each node be equipped with one add-drop multiplexer (ADM) per wavelength. Clearly, such a solution has a high ADM cost and cannot scale to more than a few wavelengths. Therefore, much of the research in this context has been on reducing the number of ADMs by grooming sub-wavelength traffic onto lightpaths that optically bypass intermediate nodes, and several near-optimal algorithms have been proposed in [3,4]. However, approaches that do not impose a hierarchical structure on the ring network may produce traffic grooming solutions, in terms of the number of ADMs and their placement, that can be sensitive to the input traffic demands.

The study in [2] was the first to present several hierarchical ring architectures and to characterize their cost in terms of the number of ADMs (equivalently, electronic transceivers or ports) and wavelengths for non-blocking operation under a model of dynamic traffic. In a single-hub ring architecture, each node is directly connected to the hub by a number of lightpaths, and all traffic between non-hub nodes goes through the hub. In a double-hub architecture, there are two hub nodes diametrically opposite to each other in the ring. Each node is connected to both hubs by direct lightpaths, and non-hub nodes send their traffic to the hubs for grooming and forwarding to the actual destination.

A more general hierarchical ring architecture was also proposed in [2]. In this architecture, shown in Fig. 1, ring nodes are partitioned into two types: *access* and *backbone*. The set of wavelengths is also partitioned into access and backbone wavelengths. The access wavelengths are used to connect all nodes, including access and backbone nodes, in a point-to-point WDM ring that forms the first level of the hierarchy. At the second level of the hierarchy, the backbone wavelengths are used to form a point-to-point WDM ring among the backbone nodes only. This hierarchy determines the routing of traffic between two access nodes as follows. If the two access nodes are such that there is no backbone node along the shortest path between them, their traffic is routed using single-hop lightpaths over the access ring along the shortest path. Otherwise, suppose that b_1 and b_2 are the first and last backbone nodes, respectively, along the shortest path between two access nodes a_1 and a_2 (note that b_1 and b_2 may coincide). Then, traffic from a_1 to a_2 is routed to b_1 over the access ring, from there to b_2 over the backbone ring, and finally over the access ring to a_2.

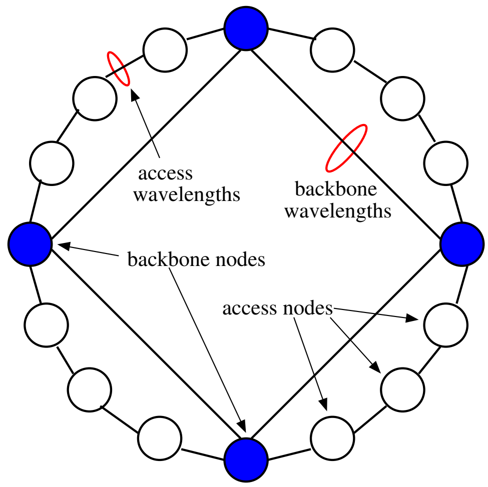

Fig. 1. Hierarchical ring architecture with 12 access and 4 backbone nodes.

A similar hierarchical ring structure was considered in [14], and it was shown that using local (access) and bypass (backbone) wavebands, *P*-port dynamic traffic (in which each node is allowed to send and receive at most *P* wavelengths worth of traffic) can be supported with a minimum number of wavelengths.

A different hierarchical approach for grooming sub-wavelength traffic in ring networks was introduced in [15]. Specifically, the *N* ring nodes are grouped into *K* *super-nodes*, where each super-node consists of several consecutive ring nodes, as shown in Fig. 2. The idea behind this partitioning is to pack (groom) all traffic from some super-node *x* to another super-node *y* onto lightpaths that are routed directly between the two super-nodes, bypassing intermediate nodes and hence, reducing the number of ADMs required. The study considered both uniform and distance-dependent traffic patterns, and, for each pattern, derived the number *K* of super-nodes, as a function of the number *N* of ring nodes and the granularity $C \geqslant 1$ of each wavelength, so as to minimize the number of ADMs; the granularity *C* is the number of unit traffic components that can be carried on a single wavelength.

Finally, [2] also proposes the decomposition of a ring into contiguous segments; these are similar to the super-nodes of [15] but are referred to as *subnets*. The ring network is organized in a hierarchical manner as a tree of subnets, where the root of the tree corresponds to a