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# Analysis of multi-hop traffic grooming in WDM mesh networks

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ABSTRACT

Traffic grooming is an essential functionality of WDM optical networks to provision multi-granularity subwavelength connections . Depending on the number of lightpaths allowed in a connection route, traffic grooming can be classified as single-hop traffic grooming (SH-TG) and multi-hop traffic grooming (MH-TG). MH-TG is more general and resource-efficient than SH-TG, because it allows connections from different source–destination pairs to share the bandwidth of a lightpath. In this paper, we propose a MH-TG algorithm, namely the fixed-order multi-hop (FOMH) grooming algorithm, based on the fixed-alternate routing approach. We introduce the grooming node selection (GNS) problem in MH-TG and propose three grooming policies, namely exhaustive sequential (ES), limited-hop sequential (LHS) and load sharing (LS) policies, to address the GNS problem. These policies represent different trade-offs among blocking probability, computational complexity and transceiver requirements. Given that the analysis of MH-TG is a relatively unexplored area, we propose an analytical model to evaluate the blocking performance of MH-TG using FOMH and the LS grooming policy. To address the multi-layered routing and multi-rate connection characteristics of traffic grooming, we introduce a novel multi-level decomposition approach in our analytical model which decomposes traffic at four different levels, namely alternate path, connection route, lightpath and link levels. The model also addresses various factors that affect connection blocking probability. These factors include wavelength continuity constraint, channel continuity constraint and route dependence. The Erlang fixed-point approximation method is used to solve the analytical model. Numerical results show that analytical results match well with simulation results. We also evaluate the effect of the grooming policies, the number of virtual hops (lightpaths) within a connection route and the number of alternate paths on the performance of the grooming algorithm.

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## 1. Introduction

THE rapid growth of the Internet requires large amounts of bandwidth. Wavelength division multiplexing (WDM) technology has the potential to meet this need by allowing simultaneous transmission of traffic on multiple wavelengths in a fiber. A wavelength-routed network (WRN) based on WDM technology is deemed as a promising candidate for the core network of the next-generation Internet.

Traffic grooming [25] addresses the gap between the bandwidth capacity of wavelengths and the bandwidth requirement of connections. With the advances in optical technology, the capacity of a single wavelength has reached OC-192 (10 Gbps) and beyond. On the other

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hand, the bandwidth of a connection request (such as SONET circuits, IP/MPLS label switched paths) may be less than that, possibly OC-3 (155 Mbps) or even lower. To make efficient use of the wavelength bandwidth, traffic grooming [1–6] is needed to pack connections at sub-wavelength granularities effectively onto wavelength channels.

In a WRN, the physical topology is a set of OXC nodes connected by fiber links. A wavelength path is referred to as a lightpath, which may span several fiber links in the physical topology. A lightpath uses a wavelength on each fiber link along its path. All the lightpaths form the virtual topology. The multi-granularity subwavelength connections are carried over the virtual topology. A connection may traverse several lightpaths along its path and uses a portion of the bandwidth of each lightpath it traverses. Fig. 1 illustrates two lightpaths and a connection in a SONET over WDM optical network. Note that a connection must originate and end in the electronic domain, which is at the digital cross-connect (DXC) in this case. In IP over WDM networks, the DXCs in Fig. 1 are replaced with IP/MPLS routers.

Traffic grooming can be classified as single-hop traffic grooming (SH-TG) and multi-hop traffic grooming (MH-TG). SH-TG restricts a connection to use a single lightpath. Therefore, a lightpath can only be used by connections belonging to the same source and destination pair. MH-TG, on the other hand, allows a connection to use multiple lightpaths. Thus, the bandwidth of a lightpath can be shared by connections from different source and destination pairs.

MH-TG is the general case of SH-TG. It is more resource-efficient than SH-TG. For instance, to satisfy three connections $C_1, C_2$ and $C_3$ as shown in Fig. 2(b), SH-TG uses three lightpaths $L_1, L_2$ and $L_3$ to carry the three connections. The three lightpaths use a total of five wavelength links and their bandwidth utilization is 50%. Fig. 2(c) shows a possible MH-TG solution. The three lightpaths used to carry the three connections consume a total of three wavelength links and their bandwidth utilization is 100%.

In this work, we analyze the performance of MH-TG in WDM optical networks. We first propose the fixed-order multi-hop (FOMH) grooming algorithm for MH-TG. We then introduce the grooming node selection (GNS) problem (also called the route selection problem) in MH-TG and propose three grooming policies to address the GNS problem. The three grooming policies are exhaustive sequential grooming policy (ES), limited-hop sequential (LHS) grooming policy and load sharing grooming policy (LS). We also propose an analytical model to evaluate the blocking performance of the FOMH grooming algorithm with the LS grooming policy. While all the previous works use either a link decomposition approach or a path decomposition approach, we introduce a novel multi-level decomposition approach which decomposes traffic at four different levels, namely alternate path, connection route, lightpath and link levels. The multi-level decomposition approach gives a clear picture of the traffic distribution within a network, which enables reasonable estimations and accurate analysis of MH-TG. At the link level, we present a multi-dimensional Markov Chain to obtain the channel distribution within a single wavelength link (SWL). At the lightpath level, we provide a connection rate dependent blocking analysis which addresses the wavelength continuity constraint as well as the channel continuity constraint. At the connection route level, we assume that the blocking on lightpaths within a route is independent because the lightpaths do not have any common links. At the alternate path level, we solve the blocking correlation problem of alternate routes on the same path when LS grooming policy is used. Our model is a general MH-TG analytical model which allows arbitrary hops (lightpaths) within a connection route. We conduct simulations to evaluate the performance of the proposed grooming algorithm and grooming policies. We also verified the correctness of the analytical model by comparing the analytical results with the simulation results.

The rest of the paper is organized as follows: Section 2 introduces the related work in the performance analysis of traffic grooming. Section 3 presents the FOMH grooming algorithm and the three grooming policies. Section 4 presents the analytical model. Section 5 presents simulation results and analytical results. Section 6 concludes the paper.

## 2. Related work

Performance analysis of routing and wavelength assignment (RWA) in WDM optical networks has been a research focus of the last decade [7,10–12,14–16]. The work in [7] uses the generalized reduced load (or Erlang fixed-point) approximation method [8,9] to calculate the blocking probability of WDM optical networks using fixed routing and random wavelength assignment. The same method is applied to the least loaded routing (LLR) in fully connected networks. However, the complexity of the analytical model grows exponentially with the number of hops within a path. To address the complexity problem, the work in [10] uses the inclusion–exclusion principle from combinatorics. With this technique, an independent model and a correlated model are proposed. The work in [11] proposes two adaptive RWA algorithms, PACK and SPREAD, which consider jointly routing and wavelength assignment. In addition, an overflow based analytical model for fixed alternate routing (FAR) and first-fit wavelength assignment is presented. The model uses Erlang loss formula to estimate the link probability, which requires the overflow traffic to be Possion traffic. However, as overflow traffic is bursty traffic whose variance is larger than its mean [13], it is not Poisson. The work in [12] presents a more accurate overflow model based on the Brockmeyer model [13] and a moment-matching technique, the equivalent random method [13]. While most of the previous work uses the link-decomposition approach [13], the work in [15] utilizes the path-decomposition approach [13]. A network is first decomposed into single-path subsystems. Then a Markov Chain model is proposed to analyze the blocking probability of single-paths. As the path decomposition approach naturally considers the correlation of link loads and link blocking, it is generally more accurate than the link decomposition approach.

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