G^+: Enhanced Traffic Grooming in WDM Mesh Networks using Lighttours

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***Abstract*— In this article, a new technique for grooming low-speed traffic demands into high-speed optical routes is proposed. This enhancement allows a *transparent* Wavelength-Routing Switch (WRS) to aggregate traffic en route over existing optical routes *without* incurring expensive Optical-Electrical-Optical (OEO) conversions. This implies that: $a)$ an optical route may be considered as having more than one ingress node (all inline) and, $b)$ traffic demands can partially use optical routes to reach their destination. The proposed optical routes are named "*lighttours*" since the traffic originating from different sources can be forwarded together in a single optical route, i.e., as taking a "tour" over different sources towards the same destination. The possibility of creating lighttours is the consequence of a novel WRS architecture proposed in this article, named "*Enhanced Grooming*" (G^+). The ability to groom more traffic in the middle of a lighttour is achieved with the support of a simple optical device named λ-monitor (previously introduced in the RingO project). In this article, we present the new WRS architecture and its advantages. To compare the advantages of lighttours with respect to classical lightpaths, an Integer Linear Programming (ILP) model is proposed for the well-known multilayer problem: *Traffic Grooming, Routing and Wavelength Assignment*. The ILP model may be used for several objectives. However, this article focuses on two objectives: maximizing the network throughput, and minimizing the number of Optical-Electro-Optical conversions used. Experiments show that G^+ can route all the traffic using only half of the total OEO conversions needed by classical grooming. An heuristic is also proposed, aiming at achieving near optimal results in polynomial time.**

***Index Terms*— Wavelength division multiplexing (WDM), lighttours, traffic grooming, lightpath, mesh network, integer linear program (ILP), photonic switching systems, optical transport network (OTN), photonic cross-connect (PXC), optimization, optical-electronic-optical conversions (OEO), lambda-monitoring.**

I. INTRODUCTION

INTERNET bandwidth requirements are increasing drastically nowadays and optical Wavelength-Division-Multiplexed networks (WDM) are designed to satisfy these requirements. WDM networks usually route traffic demand by means of *lightpaths*. A lightpath is an end-to-end (fully) optical route between two Wavelength-Routing Switches (WRS), not necessarily neighbors, that spans over several fibers using a wavelength in each fiber.

Although fibers can be demultiplexed into several wavelengths to route traffic more efficiently, user demands are much below the capacity of a wavelength. Therefore, a single lightpath is used to route several low-speed demands (sub-wavelength demands). In this context, low-speed demands are said to be *groomed* into high-speed wavelengths channels [1]. In addition, to improve resource utilization, sometimes more than one consecutive lightpath is used to forward a single demand. Therefore, a lightpath can forward several demands together and a demand can be forwarded by different consecutive lightpaths. When a demand changes from one lightpath to another, packets need to be converted from optical signal to electrical data in order to decide on the next lightpath to be taken. Once this decision is made, packets need to be re-converted from electrical data to the optical signal so that they can be forwarded optically. These Optical-Electro-Optical (OEO) conversions are usually avoided by network operators because more network resources (e.g., transmitters and receivers) are needed to regenerate optical signals. Moreover, OEO conversions could delay traffic since traffic flowing must be processed and queued in an electronic switch (EXC). Clearly, the way in which traffic is groomed and routed affects the quality of service of demands and network throughput. This problem is known as the TRAFFIC GROOMING, ROUTING AND WAVELENGTH ASSIGNMENT (GRWA) problem [2] and it is described in §II, being the main subject of this article.

In this article, a novel architecture for grooming low-speed traffic demands into high-speed fully-optical routes, named *Enhanced Grooming* (G^+), is proposed and described in §III. The proposed architecture, G^+, allows a *transparent* WRS to aggregate more traffic over optical routes (lighttours) *without* incurring any OEO conversions for the traffic being forwarded through it. Since G^+ can also be configured to forward traffic in the same way as classical grooming, its optimal solution to the GRWA problem incurs at most the same amount of resources as classical grooming, under the same conditions. Therefore, the performance of several metrics is expected to improve under G^+. In this article, two metrics related to the GRWA problem are highlighted:

- *Throughput*. The capacity used in every wavelength of a lightpath is the same. In contrast, lighttours may increase

Manuscript received April 14, 2006; revised Dec. 1, 2006. This paper was supported by the Department of Universities, Research and Information Society (DURSI) of the Government of Catalonia, European Social Funds (2005-SGR-00296, 2006-BE-00272 and, 2006-FIR-00109), and also by the Spanish Science and Technology Ministry under contract TIC2003-05567 and, the COST project action number 293: *Graphs & Algorithms in Communication Networks*.

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Digital Object Identifier 10.1109/JSAC.2007.070615.

the used capacity, since more traffic can be added en-route. This allows lighttours to use wavelength capacity more efficiently. Therefore, network bandwidth utilization can be improved.

- *Number of OEO conversions*. Because G^+ reduces the number of OEO conversions, delay due to electrical packet queueing can be reduced, and traffic transmission rates can be improved.

Other advantages over the classical architecture can be foreseen as well; for instance, a reduction in capital expenditures. Since G^+ allows for grooming of additional traffic in the middle of an optical route, fewer traffic demands need new optical routes. Therefore, given a traffic matrix, G^+ may use less wavelengths (colors) and optical transmitter/receiver devices than the classical grooming scheme. This could lead to savings on capital expenditures (CAPEX) and/or better throughput in the network. Although capital expenditures were not considered in the performance evaluation section of this article, it can be seen in the simulation results that reductions can be achieved. A comprehensive analysis of this network dimensioning problem is left for future research.

Solutions to instances of the GRWA problem, obtained by formulating it as a Zero-One Integer Lineal Programming (ILP), using both classical grooming and the proposed G^+ are presented. Different optimization objectives can be considered. A detailed description of this model is presented in §IV, and its simulation results are presented in §V. Since ILP problems are NP-complete, an heuristic for solving the GRWA problem using G^+ and achieving near-optimal solutions in polynomial time is proposed in §VI and its performance is studied in §VII. Finally, in §VIII, conclusions regarding the proposed architecture, model and heuristic are summarized, together with proposals for future work.

II. The Multilayer GRWA Problem

In this section, an outline of the Traffic Grooming, Routing and Wavelength Assignment problem (GRWA) is given and the most relevant contributions are cited. The traffic grooming problem was initially studied in the context of ring networks (e.g., [3] and [4]) and, subsequently, it has also been widely studied in the context of mesh networks, which is the scenario considered in this article. The GRWA problem can be described as follows:

Given: A traffic demand matrix (Λ) and a description of the network topology including: a) the graph of the topology ($G'(V, E')$), b) the number of transmitters (T_j) and receivers (R_j) for each node $j \in V$ and, c) the wavelengths that each link $(i, j) \in E'$ can be demultiplexed into (W),

Find: A set of optical routes and a set of routes over these that satisfies all (or part) of the traffic demand matrix. In the following, related work regarding solutions to the GRWA problem in mesh networks with the classical WRS architecture is discussed. Due to space constraints, only a representative selection of the related literature is mentioned.

Xin *et al.*, in [5], proposed an analytical model for traffic grooming of dynamic client traffic in WDM optical mesh networks assuming no wavelength conversion.

Yao and Ramamurthy, in [6], presented a model for representing WDM optical mesh networks with relaxed wavelength continuity constraints, a method to create light paths and a grooming algorithm based on their proposed model.

Banerjee and Mukherjee, in [7], studied the GRWA problem on WDM mesh optical networks with the wavelength continuity constraint by proposing an elegant ILP model in which the total number of transponders needed in the network is minimized.

Hu and Leida, in [8], consider the same GRWA problem, however, treated it differently. The problem was split into Grooming and Routing and Wavelength Assignment subproblems. The former solved with an ILP, while the latter was solved by means of an algorithm.

Similarly, Zhu and Mukherjee, in [2], study the GRWA problem under the same assumptions, however, they focus on maximizing the total network throughput. Several fast heuristics were proposed and evaluated. In [9], the same authors summarize four different WRS architectures for traffic grooming in an optical WDM network under a dynamic traffic environment.

Although the GRWA problem has been widely studied in recent years using the classical grooming architecture, few have studied it under a different WRS architecture. In this article, the GRWA problem is tackled considering a different WRS architecture that takes the classical solution beyond its current limitations.

III. G^+ Network Architecture

In this section, the basics of G^+ are explained. In §III-A, a brief explanation is given on how a classical WRS handles lightpaths. Then, in §III-B, a different node architecture for metro ring networks (RingO) is explained. Using these, a hybrid architecture, G^+, is proposed in §III-C for handling lighttours. In §III-E, the proposed architecture is compared with light-trail's. Finally, assumptions for solving the GRWA problem using G^+ are presented in §III-F.

A. The Classical Lightpaths

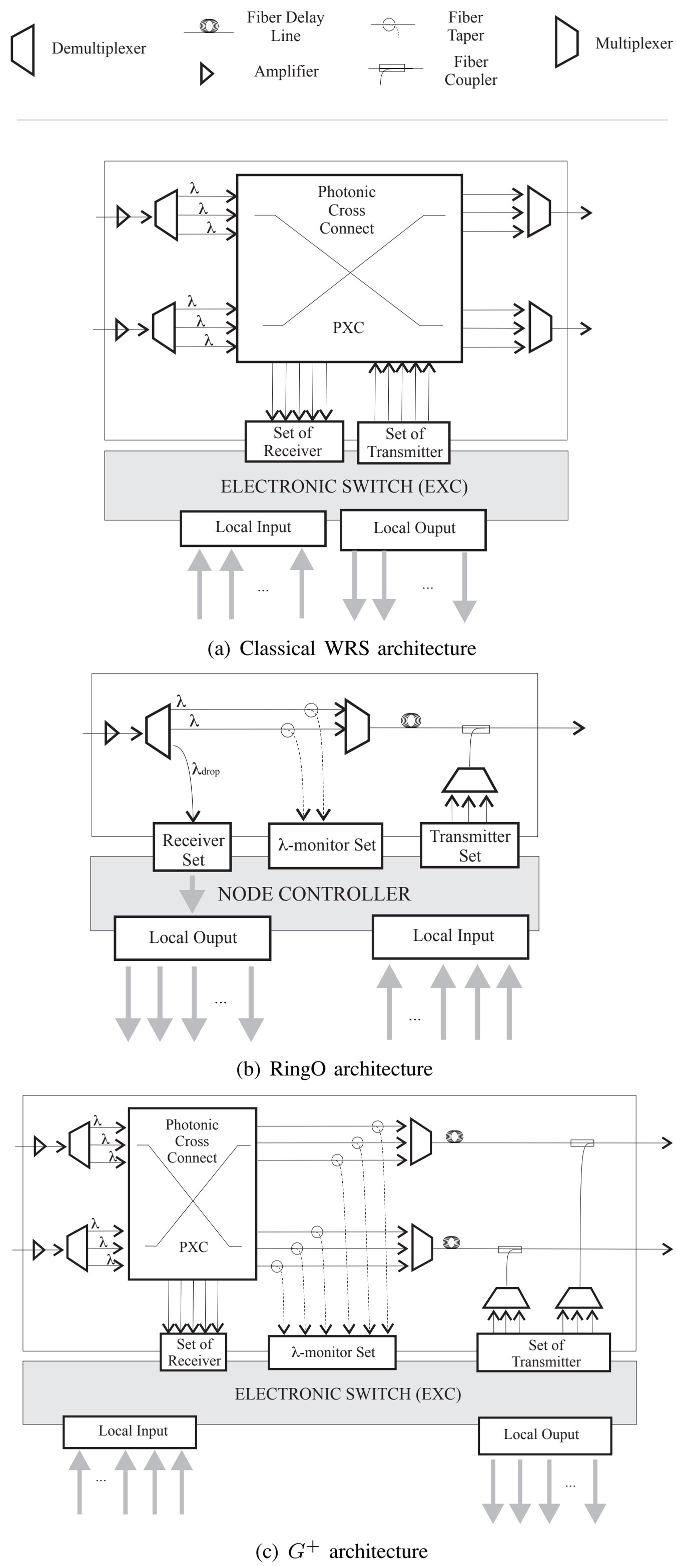
As mentioned, lightpaths are end-to-end optical connections established between pairs of WRSs in an optical network. In order to allow for a large set of lightpath configurations in a network, a typical WRS architecture must both optically forward lightpath traffic to other WRSs without making OEO conversions and transmit (or receive) optical traffic over (or from) a lightpath. Fig. 1(a) shows the classical WRS architecture aimed at working with lightpaths at wavelength granularity, which works as follows:

- Every single fiber is first demultiplexed into a set of W wavelengths.
- All the wavelengths coming from different fiber ports traverse a Photonic Cross Connect (PXC) device. This device may either redirect wavelengths to the Electronic Switch (EXC) or optically switch wavelengths fibers and/or colors to outgoing fibers.
- The wavelengths going to the EXC are redirected to a set of receivers that converts the wavelengths to the

electronic domain. This electronic traffic needs further electronic processing.

- The EXC can either take this traffic out of the WSR to local electronic equipments attached to low-speed ports, or queue it electronically for further optical forwarding through another wavelength. This decision is made based on the electronic packet headers.
- The incoming traffic to the WRS arriving from low-speed ports is queued locally together with dropped wavelengths traffic in the EXC.
- Traffic queued electronically is retransmitted over a wavelength using a transmitter.
- All outgoing wavelengths are multiplexed to their corresponding fiber.

For short, this classical architecture is abbreviated as 'G' in order to differentiate it from the proposed architecture, G^+ (to be explained in §III-C). For more details about classical WRS architecture, the reader is referred to [9].



(a) Classical WRS architecture

(b) RingO architecture

(c) G^+ architecture

Fig. 1. G^+ and related architectures.

B. The RingO Architecture

RingO is a ring optical packet WDM network designed for metro applications. Although the RingO architecture has been recently improved [10], this article uses one of its first versions, summarized here, since it fits better with G^+ needs.

In RingO, there is only one fiber connecting all nodes. The fiber can be demultiplexed into $|W|$ wavelengths. Every node receives its traffic in the ring by dropping one fixed wavelength of the fiber; no other node is allowed to drop that particular wavelength in the ring. All nodes that want to transmit to a specific node, tune their transmitter to that particular wavelength. Therefore, RingO allows only up to $|W|$ nodes in the network.

To prevent traffic contention in the ring, RingO works under the following assumptions: $a)$ the network transmits optical packets in fixed time-slots, $b)$ packets are optically coded with a fixed length, $c)$ higher layers are able to segment and reassemble optical packets, and $d)$ the tuning times of the transmitter are smaller than the slot duration.

Furthermore, RingO nodes are equipped with a λ-monitor device that allows it to check whether packets are being transmitted over a particular wavelength (λ) or not. The λ-monitor device is completely optical and very simple, and hence, fast. It only senses light passing through. If a λ-monitor device advises that a wavelength is free in a particular time slot for packet insertion, the RingO node may optically inject more traffic into it. Note that the existing traffic flow in this wavelength channel is not disturbed.

The architecture of a RingO node can be depicted in Fig. 1(b), which works as follows:

- The incoming fiber signal to a node is first amplified and then demultiplexed into a set of W wavelengths.
- One of the wavelengths (λ_{drop}) is dropped since it is traffic for that node.
- The rest of the wavelengths are tapped so that a fraction (10%) of the light passing through it is sampled.
- The tapped fraction of the power in every wavelength is analyzed by the λ-monitor device (in the λ-monitor set). The device only detects the received average power on a slot-by-slot basis in order to determine whether packets are passing through that particular wavelength.
- The incoming traffic to a node arriving from low-speed port(s) is queued locally.
- The node controller, based on the information the λ-monitor device provides, may inject more optical packets (queued previously in the electronic domain), by means

of a tunable transmitter, into that free slot.

- The transmitters are connected to a multiplexer so that new traffic can be injected directly into the fiber.
- The existing data carried by the fiber is delayed. Therefore, the node controller decisions can be synchronized and no contention occurs in the optical domain.

With RingO, existing traffic going through a wavelength does not need to be buffered electronically (no need for OEO conversion for existing traffic) in order to add more low-speed traffic. Simply, a node looks for a space (a time slot) between optical packets to allocate more traffic in the wavelength.

The RingO architecture also efficiently combines the advantages of electronic and optical technologies. The aggregated bandwidth is managed in the photonic (optical) domain, while packet queueing is managed in the electronic domain (making the proposed architecture free from expensive optical buffers).

Since this article focusses on showing the improved performance achieved by lighttours in the GRWA problem, the analysis of some details of the RingO architecture, such as optical signal codification, control plane or medium access control protocols, are out of scope. The reader is referred to [10] for these details.

C. The Proposed WRS Architecture: G^+

Considering both the G architecture supporting lightpaths and the RingO architecture, a hybrid architecture (named G^+) is proposed with the objective of improving current traffic grooming techniques.

G^+ takes advantage of the wavelength switching flexibility in G for mesh networks and the way traffic is added to wavelengths (without incurring in OEO conversions for the existing traffic in the wavelength) in RingO. This is accomplished by using the RingO node architecture as a base and adding a photonic cross connect (PXC) device just before the λ-monitor. The G^+ WRS architecture is shown in Fig. 1(c).

The G^+ architecture works under the same assumptions as RingO's. WRSs transmit information using optical packets of fixed length, each corresponding to a time-slot (hence time-slots are also fixed). However, unlike optical label switched technologies (e.g., Optical Packet Switching [11], Optical Burst Switching [12], or Photonic Slot Routing [13]), the proposed optical architecture is *not optical packet (burst) switched*. In G^+, packet headers are not read en route and hence, optical packet forwarding decisions are not made separately for each packet in the same wavelength. This simplifies the node architecture since the switching decisions are made at wavelength granularity and there is no need for optical buffers or any other scheme for solving contention in the optical domain.

A G^+ WRS works as follows:

- Every single fiber signal is first amplified and then demultiplexed into a set of W wavelengths.
- All the wavelengths coming from different fiber ports traverse the Photonic Cross Connect (PXC) device. This device may either redirect wavelengths to the Electronic Switch (EXC) or switch wavelengths from one fiber to another fiber.
- The wavelength going to the EXC (dropped wavelengths) are decoded by an array of receivers which converts the wavelengths to the electronic domain. This electronic traffic is processed.
- The EXC can either take this traffic out of the WSR to local electronic equipments attached to low-speed ports, or queue it electronically for further optical forwarding using another wavelength. The forwarding decision is made using the underlying higher layer protocol information.
- The incoming traffic to the EXC arriving from low-speed ports is queued locally together with dropped wavelength traffic.
- The remaining wavelengths in the optical domain are tapped and a fraction of the light is redirected to a λ-monitor device (in the λ-monitor set).
- The λ-monitor device determines whether optical packets are transiting through a wavelength or not. This is normally performed using a DC-coupled photodiode array, a capable PXC, or a capable Amplifier.
- The EXC, based on the information the λ-monitor device gives, may inject more optical packets (queued previously in the electronic domain) into that free slot by means of a set of transmitters lasers[1].
- The transmitters are connected to a set of multiplexers, so that new traffic can be injected directly into an outgoing fiber using an appropriate color.
- The existing data carried in the fiber is delayed so that the EXC decisions are synchronized and no contention occurs in the optical domain.

The detection of free slots in a wavelength is done by the λ-monitor device. This simplifies synchronization among the WRSs in the optical route. Without a λ-monitor device, the only way to inject optical packets in a free slot would be through precise clock synchronization among all WRSs, as in SONET/SDH [14]. This does not imply that G^+ does not require synchronization, but that some degree of loose synchronization using guardbands is used.

Forwarding of electronic packets is performed using the Generic Multi-Protocol Label Switching architecture [15]. Therefore, each of the optical fixed size packets must have an encoded label[2]. Packets-to-slots assignment is made statistically. Optical packet framing issues are not addressed in this article.

Although the size of a label as well as guardbands is supposed to be small, these could represent a minor drawback in the performance of the architecture when compared to lightpaths. Even though a small amount of overhead can be introduced, modeling label sizes and guardbands is out of scope for the grooming problem *per se*. Therefore, they are left for further studies.

D. Lighttours Properties

As stated initially in this article, the proposed enhancement allows a transparent WRS to aggregate traffic over optical

[1]The decision of using fixed or tunable lasers depends on the network requirements and is left for further studies.

[2]Coupling the G^+ architecture with SONET is a subject for further studies.

TABLE I
COMPARISON BETWEEN CLASSICAL GROOMING (G) AND G^+.

Performance Metric	Classical	G^+
Num. of Wavelengths Used	3	3
Wavelength Capacity Wastage	OC-21	OC-3
Max. Num. of Virtual Hops	2	1
Total Num. of Virtual Hops	5	3
Total Receivers Used	3	1
Total Transmitters Used	3	3
Num. of OEO Conversions	2	0

routes without incurring any OEO conversions (like RingO does) for the existing traffic in the optical route. For example, if an optical route follows the path $s \rightarrow \alpha_0 \rightarrow \alpha_1 \ldots \alpha_n \rightarrow d$ - where s is the starting WRS of the optical route and d the destination or final WRS - then, our scheme allows WRSs $\alpha_i,\ 0 \leq i \leq n$, to add more traffic without "breaking" the optical route (if the wavelength has enough bandwidth). Therefore, the G^+ "lightpaths" are able to make a *tour* over different traffic source WRSs and inject (en-route) their optical packets in the same optical route. We name the optical route resulting from the G^+ architecture a *Lighttour*. Lighttour properties are discussed through the rest of this section. The following example is given to illustrate some of its properties.

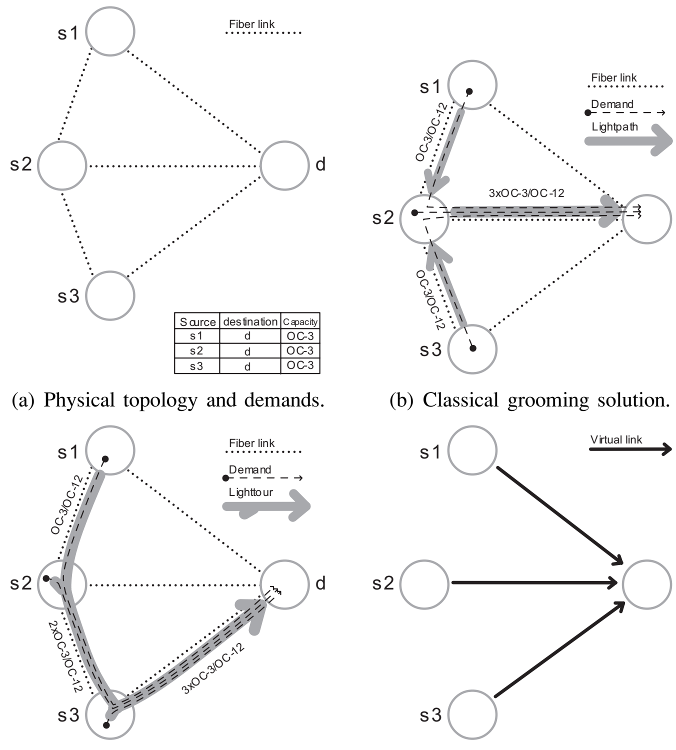
In Fig. 2(a), a network topology consisting of 4 WRSs and 5 bidirectional fiber links is shown. Fiber links can span one wavelength each. Each wavelength channel has capacity OC-12[3], but all source WRSs ($s1$, $s2$ and $s3$) only need a capacity of OC-3 to transmit to WRS d. Assume that the destination WRS d has only one available receiver. For this scenario, the best solution that classical grooming (G) may offer is to create 3 lightpaths (Fig. 2(b)), one each from $s1$ and $s3$ to $s2$, and another from $s2$ to d. This implies that there are two OEO conversions at WRS $s2$ for the demands coming from $s1$ and $s3$, therefore requiring two receivers at $s2$. In contrast, using G^+ (Fig. 2(c)) the demands can be routed with a single lighttour. Using this single lighttour ($s1 \rightarrow s2 \rightarrow s3 \rightarrow d$), the demands from $s2$ and $s3$ follow only a portion of the lighttour, i.e., they are not routed end-to-end in the lighttour. This leads to an improvement in the way the resources are used. Table I lists the results for various performance metrics for classical grooming and G^+. For instance, using G^+, there are 2 available receivers in the network (both at $s2$) and, as a consequence, less OEO conversions are needed.

Next, three properties that differentiate lighttours from lightpaths are discussed.

Fact 1 (Asymmetric Bandwidth Utilization in a Route): The bandwidth utilization of a lighttour increases over the route it takes since more traffic is added along its route. On the other hand, lightpath utilization is the same in all the wavelengths it takes.

Fact 2 (Many-to-One Transmitters-Receivers Coupling): While classical grooming uses one transmitter and one receiver per lightpath, G^+ may also require the use of one receiver, but possibly more than one transmitter per lighttour, emulating several consecutively-connected lightpaths at a time.

[3]OC-1 (optical carrier one) is equivalent to a SONET line with transmission speed of 51.84 Mbps using optical fiber.



(a) Physical topology and demands. (b) Classical grooming solution. (c) G^+ solution. (d) Lighttour virtual topology.

Fig. 2. Difference between classical grooming (G) and G^+ solutions.

In G^+, if a lighttour uses k transmitters, it does so because it is adding more traffic onto the lighttour along the path (in $k-1$ intermediate transparent WRSs). With classical grooming, the same k transmitters would be needed, while k wavelengths and k receivers might be needed as well.

Fact 3 (One-to-Many Lighttours–Virtual-Links Mapping): Since lighttours forward traffic from many WRS to a single one, a single lighttour could be seen as multiple virtual links in a virtual topology.

For instance, in Fig. 2(d), the virtual topology created by a single lighttour can be seen. It consists of three virtual links, since its corresponding lighttour connects three source WRSs to the same destination.

Although a proper discussion on synchronization issues is not addressed in this article, it should be noted that the transmission delay of lighttour packets injected in the middle of a wavelength (e.g., while WRS seeks for free slot) is the same as that caused by grooming these demands at the source of a lightpath: the source node would have to queue traffic in order to transmit it through the lightpath. This is considering that the propagation time in fibers is insignificant compared to the processing time of electronic packets.

E. Related Network Architectures

Another architecture that improves wavelength utilization in WDM mesh optical networks is *light-trail* [16]. Light-trails are unidirectional optical routes crossing several optical nodes, such that any node in the light-trail can send information to any of its downstream nodes without having to reconfigure. The wavelength is shared in time and the medium access is arbitrated by a control protocol among the optical nodes that try to transmit data simultaneously.

A light-trail acts as an optical bus. For instance, let us assume a light-trail is created starting from node $s1$, passing through $s2$ and $s3$, and ending at d in Fig. 2(a). If $s1$ and $s2$ both request to communicate with d using the light-trail, they are not able to do it at the same time. One of them, say $s1$, uses the light-trail to transmit to d; and then, when the light-trail is completely free (the transmission is ended or interrupted), the other node, say $s2$, may use it.

The main difference between lighttours and light-trails lies in the partition of the wavelength in time-slots. The fact that light-trails create an optical bus makes them depend on the control plane for multiplexing the subwavelength connections. This could delay downstream transmissions, since the trail has to be empty before transmission.

We consider that light-trails are suited for bursty traffic where transient connections are needed and the requirements for providing quality of service are low. On the contrary, lighttours are more suitable for permanent connections with higher quality of service requirement for subwavelength traffic.

F. Assumptions

In the following sections, two different proposals (model and heuristic) are given to solve the GRWA problem. The following assumptions hold for the solutions proposed in this article:

- *Wavelength Continuity:* WRSs are not able to convert a wavelength in an input fiber to another wavelength for an output fiber, i.e., there are no wavelength conversion capabilities. Assuming full wavelength conversion capabilities makes the model simple.
- *WRS Connectivity:* There is at most one fiber link, in each direction, between every pair of WRSs. Moreover, all fibers have the same capacity.
- *Wavelength Multiplexing:* Fibers have the same number of wavelengths.
- *Multi-path:* One optical route (lighttour or lightpath) uses one wavelength. However, multiple optical routes may exist between two pair of WRSs if they use different wavelength channels.
- *Physical Hops and Optical Route Length:* All optical routes have limitations in physical hops and length. The reason is simple, optical signals need amplification and optical channels induce noise in the signal. Although these two parameters are considered in §IV, none of them affect the results in our simulations[4].

IV. The Multilayer G^+ Model

Most classical grooming models consider three separate pairs of node-indexes for distinguishing between fiber links, virtual links, and source/destination WRSs of a demand. These models have two main sets of variables: one for lightpath routing (virtual topology) over existing fiber links, and another for routing demands over the lightpaths [2][7]. Therefore, most of the variables are associated with two pairs of indices. These models usually route lightpaths over fibers and traffic demands over lightpaths as two routing subproblems considered together. One advantage that lightpath modeling has is that a lightpath is mapped directly to just a single virtual link, making routing over virtual links easier [17].

Because of *Fact* 3 described in §III-C, the traditional scheme of two independents routing submodels is difficult to apply. This led us to re-consider the way in which traffic grooming had been modeled thus far. The proposed model works slightly differently. It routes traffic demands over the physical topology *if* there exists a lighttour spanning it.

In the GRWA, different objectives can be considered. For instance, in a resource constrained network, it is desirable to maximize the total traffic that can be routed over the network. On the contrary, given a minimum desired throughput, it can also be desirable to minimize the number of resources for routing the traffic.

A. An ILP Formulation for Multi-hop Enhanced Grooming

In this subsection, an ILP model for the multilayer problem where demands can be routed using several consecutive lighttours (i.e., multi-hop grooming) is proposed.

The following list are the indices used by the variables of the ILP proposed.

Indices:

i,j,k	WRSs in the network.
m	A demand that needs to be routed.
t	A lighttour in the network.
w	A wavelength of a fiber.

The model parameters are listed next, i.e., input data or constants.

Parameters:

Λ^m	Traffic demand m[5].
Δ_j^m	1 if WRS j is the destination for demand m, -1 if it is its source and 0 otherwise.
$F_{(i,j)}$	The physical (fiber) distance between nodes. It is assumed that the minimum distance between any connected pair of nodes is 1. A disconnected pair of nodes has distance 0.
C	Capacity of a wavelength[5]. It takes positive integer values.
T_i	Number of transmitters in WRS i. It takes non-negative integer values.
R_i	Number of receivers in WRS i. It takes non-negative integer values.
H	Maximum number of hops allowed for a lighttour.
L	Maximum lighttour distance allowed.

Next, we describe the decision variables for the model.

Variables:

r^m	1 if demand m has been successfully routed, 0 otherwise.

[4]Many models in the literature do not consider these two parameters.

[5]All capacities are expressed as multiples of OC-1.

$p_{(i,j)}^{m,t}$ 1 if demand m is routed through lighttour t in fiber (i,j), 0 otherwise.
$\lambda_{(i,j)}^{t}$ 1 if lighttour t uses a wavelength on fiber (i,j), 0 otherwise.
$\rho^{m,t}$ 1 if lighttour t routes demand m, 0 otherwise.
q_j^t 1 if WRS j is grooming additional traffic into lighttour t, 0 otherwise. In other words, it is 1 if a demand is being partially routed over lighttour t starting at WRS j, 0 otherwise.
$d_{(i,j)}^{t}$ 1 if link (i,j) is the last one for lighttour t, 0 otherwise.
γ_w^t 1 if lighttour t uses wavelength w, 0 otherwise.

The formulation requires *apriori* knowledge of the number of optical routes of the optimal solution. Therefore, the dimension of index t should be bounded by a large enough number such that all optical routes can be computed. In the worst case, it can be set to $\min(|E| \times |W|, |M|)$, where E, W, M represent the set of indices for links, wavelengths and demands respectively.

All the variables used in the model are binary. Therefore,

$$p_{(i,j)}^{m,t}, l_{(i,j)}^{t}, d_{(i,j)}^{t}, \rho^{m,t}, q_j^t, r^m, \gamma_w^t \in \{0,1\} \tag{1}$$

Among all the objectives discussed for the multilayer problem, maximizing throughput is considered first.

MAXIMIZE:

$$\sum_m \Lambda^m \cdot r^m \tag{2}$$

where (2) is the amount of *routed* traffic. Therefore, the expression maximizes the total throughput. The solver will try to satisfy the demands by assigning the value 1 to the r^m variables with higher Λ^m whenever possible.

SUBJECT TO:

a) Routing Constraints:

$$\sum_{i,t} p_{(i,j)}^{m,t} - \sum_{i,t} p_{(j,i)}^{m,t} = \Delta_j^m \cdot r^m, \qquad \forall m, j, \tag{3}$$

$$p_{(i,j)}^{m,t} + p_{(j,i)}^{m,t} \leq 1, \qquad \forall i,j,t,m \tag{4}$$

$$\sum_i \lambda_{(i,j)}^{t} \leq 1, \qquad \forall j,t \tag{5}$$

$$d_{(i,j)}^{t} + \rho^{m,t} - p_{(i,j)}^{m,t} \leq 1, \qquad \forall i,j,m,t \tag{6}$$

$$p_{(i,j)}^{m,t} - p_{(j,k)}^{m,t} + \lambda_{(j,k)}^{t} \leq 1, \qquad \forall i,j,k,m,t \tag{7}$$

where (3) and (4) are the basic flow conservation constraints for a demand (regardless of the lighttour). (5) assures that each lighttour is linear-shaped, i.e., not a tree. (6) forces the use of the last link of a lighttour t for a demand m, if the demand is being forwarded in t.

The last constraint, (7), relates to the base of the G^+ model. It allows a demand to be routed through a portion of the lighttour. This means that if a demand is routed in a link (i,j) using a lighttour and this lighttour continues to be active in (j,k) (for any k), then the demand must be routed in (j,k) using the same lighttour. Therefore, if a demand "wishes" to get routed through a lighttour ($s \rightarrow \alpha_0 \rightarrow \alpha_1 \ldots \alpha_k \ldots \alpha_n \rightarrow d$) starting at WRS α_k, the demand must follow the lighttour route from α_k until the end ($\alpha_k \rightarrow \alpha_{k+1} \ldots d$) regardless of the unused portion of the lighttour ($s \rightarrow \alpha_0 \ldots \alpha_k$).

Note that this avoids the need to handle special flow conservation constraints - except (5) - for the $\lambda_{(i,j)}^{t}$ variables. This is because every pair $p_{(i,j)}^{m_1,t}$ and $p_{(i,j)}^{m_2,t}$ is tied down in the same link if the lighttour t is "activated" in (i,j) (i.e., $\lambda_{(i,j)}^{t} = 1$).

b) Wavelength Continuity Constraint:

$$\gamma_w^{t_1} + \lambda_{(i,j)}^{t_1} + \gamma_w^{t_2} + \lambda_{(i,j)}^{t_2} \leq 3, \qquad \forall i,j,t_1 \neq t_2, w \tag{8}$$

$$\sum_w \gamma_w^t - \sum_{(i,j)} d_{(i,j)}^{t} = 0, \qquad \forall t \tag{9}$$

where (8) and (9) are the wavelength continuity constraints, i.e., these two equations prohibit wavelength conversions in the network. By limiting the left hand side of (8) to 3, two different lighttours cannot use the same wavelength on the same link. Additionally, since the index w takes a finite set of values, the number of wavelengths used in a fiber is automatically restricted.

Constraint (9) allows a lighttour to use only one wavelength. It should be pointed out that $\sum_{(i,j)} d_{(i,j)}^{t}$ is 1 if the lighttour t is being used by any demand and 0 otherwise.

c) Capacity Constraints:

$$\sum_m \left[\Lambda^m \cdot p_{(i,j)}^{m,t}\right] \leq C, \qquad \forall i,j,t \tag{10}$$

$$\sum_t q_j^t \leq T_j, \qquad \forall j \tag{11}$$

$$\sum_{i,t} d_{(i,j)}^{t} \leq R_j, \qquad \forall j \tag{12}$$

$$\sum_{(i,j)} \lambda_{(i,j)}^{t} \leq H, \qquad \forall t \tag{13}$$

$$\sum_{(i,j)} F_{(i,j)} \cdot \lambda_{(i,j)}^{t} \leq L, \qquad \forall t \tag{14}$$

where (10) limits the bandwidth used by a lighttour. Note that the constraint runs over all links since the used capacity of a lighttour varies from link to link (as mentioned in Fact 1 in §III-C). (11) and (12) bound the number of receivers and transmitters devices per WRS, respectively.

Like other optical routes, lighttours have hop and length limitations. (13) and (14) address these two aspects, respectively.

d) Relationship between Variables:

$$\sum_i p_{(j,i)}^{m,t} - \sum_i p_{(i,j)}^{m,t} - q_j^t \leq 0, \qquad \forall j,m,t \tag{15}$$

$$p_{(i,j)}^{m,t} - \sum_k p_{(j,k)}^{m,t} - d_{(i,j)}^{t} \leq 0, \qquad \forall i,j,m,t \tag{16}$$

$$p_{(i,j)}^{m,t} - F_{(i,j)} \leq 0, \qquad \forall i,j,m,t \tag{17}$$

$$p_{(i,j)}^{m,t} - \lambda_{(i,j)}^{t} \leq 0, \qquad \forall i,j,m,t \tag{18}$$

$$p_{(i,j)}^{m,t} - \rho^{m,t} \leq 0, \qquad \forall i,j,m,t \tag{19}$$

Constraint (15) increases the lower bound of q_j^t to 1 if WRS j is grooming traffic on t for any demand d. Since only one transmitter is needed to groom several demands in a WRS,

$q_j^t = 1$ regarless of how many demands are groomed by WRS j in lighttour t.

Constraint (16) defines variable $d_{(i,j)}^t$ by imposing a lower bound of 1 when j has no outgoing traffic but it has incoming traffic from i for at least one demand of t.

Constraint (17) sets an upper bound of 0 to p in those links in which there is no fiber connecting the nodes. (18) activates a lighttour link (i,j) if there is at least one demand using it. (19) registers the relationship between a routed demand and the lighttours it traverses.

B. Constraining for Classical Grooming Modeling

For classical grooming modeling, the ILP can be configured to limit the number of grooming WRSs that every lighttour has to at most one. Limiting this quantity to one creates lighttours having only one grooming WRS, the source WRS. This can be formulated by adding the following constraint.

$$\sum_j q_j^t \leq 1, \forall t \tag{20}$$

C. Other Common Constraints

A very common constraint when modeling grooming is to restrict routing of demands to one virtual hop. This way, no OEO conversions are employed but a "smaller" maximum throughput is obtained. This can be done by adding a constraint to restrict the number of lighttours associated with each demand as follows.

$$\sum_t \rho^{m,t} \leq 1, \quad \forall m \tag{21}$$

The model can also be modified to allow full wavelength conversion. In order to do so, (8) and (9) must be removed, and instead, an equation limiting the number of wavelengths per fiber should be added:

$$\sum_t \lambda_{(i,j)}^t \leq |W|, \quad \forall (i,j) \tag{22}$$

where $|W|$ is the number of wavelengths per fiber.

D. Tightening the Model

The more constraints a linear programming model has, the more time is required by the optimizer to solve it. However, regarding ILP models, sometimes by adding "dummy" and/or "redundant" constraints, that tighten the formulation, the response time can be improved (specially, considering the *Branch and Bound* process in the global search for integer solutions [18]).

Some of these redundant constraints in our model may come from binary-OR variable formulations. Logic OR-formulations between two variables are tightly coupled in our model following the rule:

$$\forall a, x_a \leftrightarrow \bigvee_b y_a^b \therefore \begin{cases} \forall a, b, & x_a - y_a^b \geq 0, \\ \forall a, & x_a - \sum_b y_a^b \leq 0 \end{cases}$$

where $\bigvee$ is an OR operator. For example, the relationship between variables $\rho^{m,t}$ and $p_{(i,j)}^{m,t}$ can be modeled tightly using (19) and

$$\rho^{m,t} - \sum_{(i,j)} p_{(i,j)}^{m,t} \leq 0, \quad \forall m, t$$

Additionly, other self-evident constraints may be considered for better ILP-tightening. For instance,

$$\sum_{(i,j)} d_{(i,j)}^t \leq 1, \quad \forall t$$

E. Considering Other Objectives

The proposed model can be adapted to other objectives. In this subsection, different objectives and their corresponding implications are considered.

1) Transmitters and Receivers: The number of used transmitters and receivers can be minimized. First, the desired throughput can be guaranteed by

$$\sum_m \Lambda^m \cdot r^m \geq \hat{\Lambda} \cdot \sum_m \Lambda^m, \tag{23}$$

where $0 < \hat{\Lambda} \leq 1$ is a constant that gives the minimum throughput to be routed.

Then, the number of transmitters and receivers can be minimized by

MINIMIZE

$$\sum_{j,t} \left[q_j^t + \sum_i d_{(i,j)}^t \right] \tag{24}$$

Since for both G^+ and classical grooming, one receiver is used for each optical route, the term $\sum_{(i,i)} d_{(i,j)}^t$ is used to count the number of receivers, while the term $\sum_{t,j} q_j^t$ counts how many nodes are injecting traffic into a lighttour, which turns out to be equivalent to the number of transmitters (even if the model is restricted to handle only lightpaths).

Since the throughput of a WDM network is proportional to the number of optical routes it can handle, minimizing this quantity may lead to solutions in which no partial route is taken, i.e., creating lightpaths even though multiple grooming nodes are allowed. Adding two transmitters to extend a lighttour will not increase network throughput as much as using one transmitter and one receiver to create a new lightpath.

2) Wavelengths: Reducing the number of used wavelengths is a common objective considered in most works. Minimizing this quantity can be achieved by fixing a desired minimum throughput, i.e., using (23) and setting as objective

MINIMIZE

$$\sum_{(i,j),t} d_{(i,j)}^t \tag{25}$$

Although this quantity could be of real interest when considering CAPEX, it was not consider in this article because it may lead to increasing the number of OEO conversions needed to route the demands.

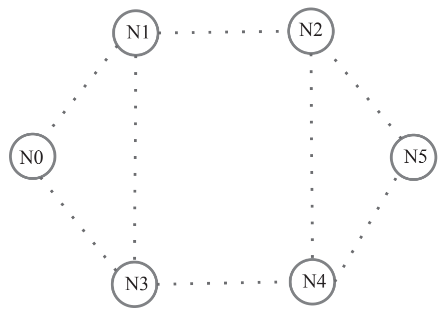


Fig. 3. Physical topology.

3) OEO Conversions: The number of OEO conversions needed to route a given minimum throughput, constrained with (23), can be minimized with:

MINIMIZE

$$\sum_{m}\left[\sum_{t}\rho^{m,t}-r^{m}\right] \tag{26}$$

The $\sum_{m_t}\rho^{m,t}$ term adds the number of virtual hops taken by the routed demands. Since the number of OEO conversions performed for a given demand is one less than the number of virtual hops needed, the term $\sum_m r^m$ is subtracted to obtain the correct value.

V. COMPARING G^+ AND CLASSICAL GROOMING: A NUMERICAL EXAMPLE

It is easy to see that G^+ will, in the worst case, behave like classical grooming with any ordinary networking objective function, since all feasible solutions for classical grooming are also feasible for G^+. However, in this section, a set of numerical solutions[6] for the ILP model proposed in §IV is presented in order to highlight the improvements achieved.

The simulation scenario (network topology and traffic demand matrix) in this section mirrors previous studies of the GRWA problem with ILPs (e.g. see [9] and [13]). The network shown in Fig. 3 is used in the simulations. It is considered that each fiber link may be demultiplexed to at most $|W|$ wavelengths and each WRS in the network has $|T|$ transmitters and receivers. The capacity of each wavelength is OC-48. Wavelength conversion is not allowed.

The traffic demand matrix is generated similarly to [9]. Each demand bandwidth may correspond to OC-1, OC-3 or OC-12. The number of OC-1 demands between any pair of nodes follows an uniform distribution between 0 and 10, OC-3 demands follow an uniform distribution between 0 and 6, and OC-12 demands follow an uniform distribution between 0 and 2. In total, 235 demands are generated with a total bandwidth equivalent to OC-585: 123 OC-1 demands, 98 OC-3 demands, and 14 OC-12 demands.

To compare the results, the model is solved twice[7]: once using lighttours and another using lightpaths[8]. Two objectives are considered for study in this section: *maximizing single-hop throughput* and *minimizing OEO conversions*.

[6]The solver used is Xpress by Dash Optimization, release 2005B for 32-bits Linux.

[7]Some solutions for the lighttours scenarios are at most 2.5% away from the optimal value, unless otherwise noted.

[8]By restricting the model as mentioned in §IV-B.

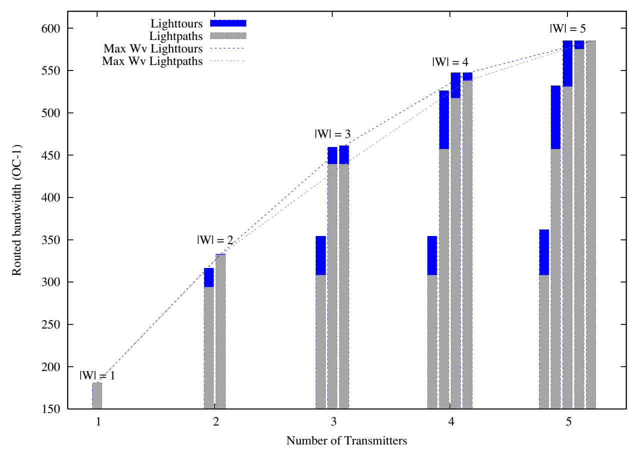


Fig. 4. Maximum throughput for G (lightpaths) and G^+ (lighttours) with single-hop routing.

A. On Throughput

In this subsection, the throughput obtained by lighttours is compared with that of lightpaths. The number of OEO conversions is constrained to its minimum (i.e., single-hop routing as mentioned in §IV-C) and the maximum throughput the network can yield is obtained. Although maximizing throughput allowing multi-hop grooming yields betters results considering either architectures, this scenario is left for further study.

The same traffic demand matrix described previously is considered in this single-hop grooming test. The number of wavelengths per fiber and transmitters (and receivers as well) are varied. The results can be seen in Fig. 4.

Simulation results show that G^+ always outperforms classical grooming with respect to throughput. The performance gain of G^+ is even more pronounced when there are either few transmitters/receivers per WRS or wavelengths per fiber (e.g., 15% more than classical grooming when using 2 wavelengths and 4 transmitters).

It should be noted that these results illustrate a possible capital expenditure reduction. This is manifested in two ways. First, when the number of transmitters is fixed, G would need more wavelengths than G^+ to achieve the same throughput. For instance, when $|T| = 5$, G would need 3 wavelengths per fiber to reach 90.8% of throughput, while G^+ only needs 2. While wavelengths represent minor savings, transmitters do not. Therefore, as a second illustration on capital expenditure reduction, consider the scenarios when the number of wavelengths is fixed. G would need more transmitters than G^+ to achieve the same throughput. For instance, when $|W| = 2$, G would need 4 transmitters per WRS (24 in total) to reach 78.4% of throughput, while G^+ outperforms it with only 3 transmitters per WRS (18 in total).

B. On OEO conversions

As explained before, even though a WRS has to wait for free slots, the proposed architecture does not incur in any extra

TABLE II
COMPARISON BETWEEN OPTIMAL SOLUTIONS USING CLASSICAL GROOMING (G) AND ENHANCED GROOMING (G^+).

Num. of Wavelength x Fiber	2		3		4	5
Grooming Type	G^+	G	G^+	G	G	G
Num. of OEO Conversions	≤18[3]	49	0	23	6	0
Num. of single-hop demands	218	186	235	212	229	235
Num. of 2-hops demands	16	49	0	23	6	0
Num. of >2-hops demands	1	0	0	0	0	0
Max. Num. of Virtual Hops	3	2	1	2	2	0
Total Transmitters Used[1]	29	20	30	24	28	30
Num. of Optical Routes[2]	19	20	18	24	28	30

[1] The total number of available Transmitters (and Receivers as well) is 30 (5 per node).
[2] The number of Optical Routes is equal to the number of Receivers Used.
[3] The number of OEO conversions is at least 7, maximum 18.

major delay for the routed traffic. Therefore, the main cause of delay is the same as in the classical architecture: OEO conversions. In this subsection, numerical examples minimizing the number of OEO conversions in different scenarios are presented.

Tightening the model as described before not only speeds up the solver (see §IV-D), but gives accurate values to most of the variables not present in the objective function[9] [18]. Hence, the number of OEO conversions (in this case) and several other metrics can be estimated.

Contrary to the previous experiment, for consistency reasons, the single-hop routing constraint is disabled in this set of experiments. The number of transmitters is fixed to 5 per WRS and the number of wavelengths is uniformly varied from 2 to 5. The solver is asked to solve the model routing *all* demands while using the minimum number of OEO conversions. The results are summarized in Table II. The columns labeled as G^+ and G refer to lighttour and lightpath solutions, respectively.

The table shows the minimum number of OEO conversions needed in each scenario and the number of demands routed using single-hop or multi-hop. In addition, the maximum number of virtual hops and the number of transmitters and receivers are also shown.

The simulations show that G^+ *can route a fixed amount of traffic using half the number of OEO conversions needed by classical grooming*. For example, at two wavelengths per fiber, G^+ uses less than 18 OEO conversions (17 demands via multi-hop routing) to route all the OC-585 traffic, while classical grooming needs 49 OEO conversions (49 demands via multi-hop routing). As supported by the previous set of experiments, when the number of wavelengths is set to 3, G^+ is able to route all traffic using single-hop, whereas G needs 5 wavelengths for the same purpose.

Since the maximum number of transmitters is almost reached for the worst case pure-lighttour scenarios (when $|W| = 2$), we believe that a lower value of OEO conversions can be achieved by increasing the number of available transmitters in the network. However, scenarios in which a fixed number of wavelengths and variable number of transmitters and receivers is used is left for further study.

It should be pointed out that while these results show that G^+ *uses* more transmitters than G, they only imply that G^+ uses the available resources (transmitters) more efficiently, as can be seen in the first set of experiments.

Other experiments show that the difference between allowing full wavelength conversions and no wavelength conversion is not significant with regards to the improvement on the number of OEO conversions, i.e., the number of OEO conversions is still reduced to half of its original value.

[9] Without tightening the model, while minimizing the number of OEO conversions, a solution could create a lighttour without routing any demand at all. Such a solution may not affect the objective function itself, however, the number of transmitters and receivers will not be close to the intended value.

VI. HEURISTIC

Obtaining the optimal solution using the model could be very expensive in terms of computational time. Hence, an heuristic capable of finding near optimal solutions for the GRWA problem in polynomial time, using G^+, is proposed in this section.

This section is divided in two parts. Initially, in §VI-A, some definitions are given and later, in §VI-B, the heuristic is described.

A. Definitions

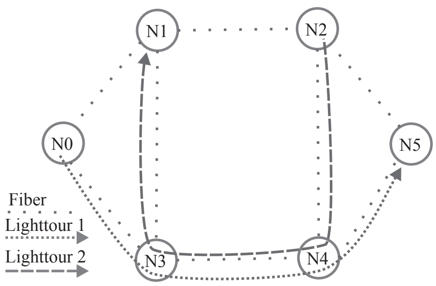
The proposed heuristic uses a special virtual topology, also proposed in this article. Although the definitions given in this section apply to both architectures, specific details and properties for lightpaths are not explored. The special virtual topology and other related concepts are detailed in this subsection.

Definition 1 (eXtended Virtual Topology - XVT): Given a physical network $G'(V, E')$ and a set of lighttours L routed over the physical topology G', an *eXtended Virtual Topology* (XVT) of G' taking L - represented now on as $G_L(V, E)$ - is a directed multi-graph created by taking all the WRSs in V, the links of the physical topology having free wavelengths, and the virtual links that map L to a common virtual topology.

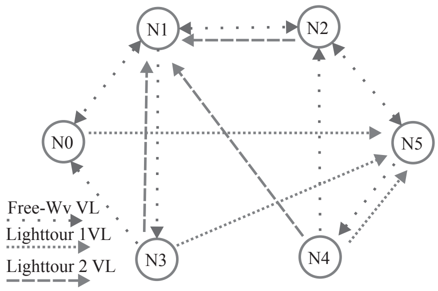
As mentioned in Fact 3, a lighttour could be mapped onto more than one virtual link. This way, if a lighttour spans over k fibers links in the physical topology, the lighttour is mapped to k different virtual links, one for each of the feasible grooming source nodes.

Definition 2 (Fiber and Lighttours Virtual Links): As our definition states, an XVT is composed of two types of virtual links: those mapped from fibers with available wavelengths, *Free-Wavelength Virtual Links* (represented with a single arrow '$\rightarrow$' in the text), and those mapped from lighttours, *Lighttour Virtual Links* (represented with a double arrow '$\rightrightarrows$' in the text).

A path over an XVT may consist of links representing either fibers or lighttours. Therefore, given a demand from s to d, finding a route over an XVT may imply taking lighttours (possibly only a portion of the lighttour) and/or using available fibers for the creation of new lighttours. This is clearly advantageous. Within a single multi-graph (the XVT), all possible means to route a demand can be considered at the same time, using only existing lighttours (a multi-hop solution), creating lighttours from raw (available) fibers (a single-hop solution), and a mixture of both (a multi-hop



(a) Physical topology with 2 lighttours.



(b) eXtended Virtual Topology (XVT).

Fig. 5. Network topology example.

solution with new lighttours). Note that the creation of an XVT is $O(n+e+n\cdot l)$, where n, e and l are the number of WRSs, physical links, and existing lighttours respectively.

Since there is a direct mapping of a WRS in a physical topology to its XVT, the number of free (unused) transmitters and receivers of a WRS can be easily handled. When a WRS in a physical network runs out of receivers, the XVT can cut off all incoming Free-Wavelength Virtual Links to the mapped WRS in the XVT. Similarly, when a WRS in a physical network runs out of transmitters, the XVT can cut off all outgoing Free-Wavelength Virtual Links and also all Lighttour Virtual Links that are not currently grooming traffic in their corresponding lighttour. This prevents the creation of demand paths requesting non-available transmitters or receivers.

Example: Consider the network in Fig. 5(a) with 6 WRSs interconnected by 8 bidirectional fiber links and 2 lighttours lt_1 and lt_2, which satisfy a set of traffic demands. Assuming that there is only one wavelength per fiber and that no WRS has run out of either transmitters or receivers, the XVT is shown in Fig. 5(b). It should be pointed out that some of the links may correspond to lighttours and others to fiber links. For example, while links $N1 \rightarrow N2$, and $N5 \rightarrow N4$ are Free-Wavelength Virtual Links, $N0 \rightrightarrows N5$, and $N4 \rightrightarrows N1$ are Lighttour Virtual Links taken from lt_1 and lt_2, respectively. In addition, note that both lt_1 and lt_2 are each mapped to 3 Lighttour Virtual Links; the former with destinations $N5$ and, the latter with destinations $N1$.

Since the proposed heuristic (explained in detail in §VI-B) is based on the shortest path algorithm, weights are given to links for setting different heuristic behaviors. The weight of a Free-Wavelength Virtual Link is represented by w_F, while the weight of a Lighttour Virtual Link is represented by w_L.

Definition 3 (Weight of Virtual Links): The relationship between these two weights affects the algorithm's objective as follows:

- *Case* $w_F \ll w_L$: a shortest path algorithm will aim at creating new lighttours to satisfy the demand (when possible), i.e., it will avoid taking existing lighttours to route the demand. Since new lighttours would be created for new demands, the number of OEO conversions could be minimized.
- *Case* $w_F \gg w_L$: a shortest path algorithm will avoid (when possible) creating new lighttours to route the demand, and will use existing lighttours to route new demands. Therefore, the number of used wavelengths could be minimized.

B. The Shortest-2-Shortest Heuristic

The GRWA is separated into two subproblems (most of the times closely tied), TRAFFIC GROOMING AND ROUTING and WAVELENGTH ASSIGNMENT for the sake of simplifying complexity. Since the simulation experiments in §V showed that the rate of the reduced OEO conversions is the same with or without the wavelength continuity constraint, we focus on solving the TRAFFIC GROOMING AND ROUTING subproblem. The WAVELENGTH ASSIGNMENT subproblem can be solved with one of the heuristics in [19].

One way to route traffic with the least number of lighttours (hence, less virtual hops and less OEO conversions) is to find lighttours crossing several sources[10]. In other words, given a destination, we find the least number of lighttours that make a *tour* over all the sources. In fact, the heuristic takes advantage of Fact 2 explained in §III-C.

The complete heuristic pseudo-code is given in Fig. 6. The heuristic has two nested loops. The outer loop (lines 3 to 24) selects a destination WRS d, which satisfies the greatest possible number of demands. The inner loop (lines 10 to 18) computes a path l over the XVT traversing several sources to d. The inner loop computes an extension of path l, named p, in each iteration such that a new source can be routed in l (the new source may be a source of several demands to d; the Λ' set in line 12). The path extension, p, is computed[11] (initially in line 8 and later in line 18 inside the loop) using a shortest path algorithm from one of the source WRSs, from the set N not yet included in the path, to the first WRS of the path l.

If there are several shortest paths going from different sources, the one demanding more bandwidth is selected. The variables $routedBw$ and $bwLimit$ keep track of the used and available bandwidth of the new route, respectively. For better efficiency, in each iteration of the inner loop, the set N is reduced so that only demands having less bandwidth than that available in the path ($bwLimit$) are considered.

[10]Fig. 2(c) intuitively illustrates this idea.

[11]The links in p, and those going to any WRS in p, are removed from G. This way, the next time the shortest path algorithm is run, the new path p cannot create a loop in l.

```
begin
  Set the resulting set as empty, L ← ∅;
  repeat
    Create an extended virtual topology G_L(V, E) considering
    the physical topology G' and the lighttours in L;
    Select WRS d as the destination of the greatest amount of
    non-routed traffic;
    Initialize lighttour path l as empty;
    Let N be the set of source WRSs with non routed demands
    to d;
    Let p be the shortest route from a WRS s ∈ N to d;
    Let routedBw ← 0 and bwLimit ← C;
    while p exists do
      Extend lighttour path l with the links in path p;
      Let Λ' ⊆ Λ be the set of demands from s to d that can
      be satisfied with bwLimit;
      Let e* be the available bandwidth of the link in l with
      the least available bandwidth;
      Increase routedBw with all the satisfied demands in Λ';
      Set bwLimit ← e* − routedBw;
      Mark all demands in Λ' as routed;
      Retain, in N, the sources demanding less than bwLimit
      units, i.e. N ← N − Λ';
      Let p be the shortest route from a WRS s ∈ N to the
      first WRS in l;
    if l ≠ ∅ then
      Let l' be the Free-Wavelength Virtual Links of l;
      Create a lighttour for each set of consecutive links in l'.
      Let L' be the set of created lighttours;
      Reduce the available capacity of all the lighttours virtual
      links in l and in L';
      L ← L ∪ L' ;
  until N ≠ ∅ and l ≠ ∅ ;
end
```

Fig. 6. Procedure S2S(G': physical network, Λ: demands)

VII. HEURISTIC PERFORMANCE

In this section, two sets of simulations of the proposed heuristic are analyzed. The first set of simulations, discussed in §VII-A, aims at showing how close the heuristic solutions are to the optimal values computed by the ILP model proposed in §IV. In all simulations shown in this section, it is assumed that WRSs perform full wavelength conversion when needed.

Since a comparison between G^+ and classical grooming was already discussed in §V, simulations of classical grooming are not described in this section.

A. How Good is the Heuristic?

In this subsection a subset of the scenarios analyzed in §V is considered. The topology (see Fig. 5(a)) and traffic demand matrix are the same.

Since our concern is to route the maximum amount of traffic using the least number of OEO conversions, the heuristic is run considering solely $w_L \gg w_F$ (scenarios varying weights are analyzed in the next subsection).

While the optimal maximum throughput is achieved using 5 transmitters per node and 2 wavelengths per fiber (see Table II), under the same circumstances, the heuristic routes 70.7% of total demanded capacity. However, if the number of wavelengths per fiber is increased to 4, the heuristic achieves 92.3% of the maximum throughput using the same number of transmitters. The remaining 8.7% is obtained if the network is provided with 3 additional transmitters per node, i.e., 8 transmitters per node in total.

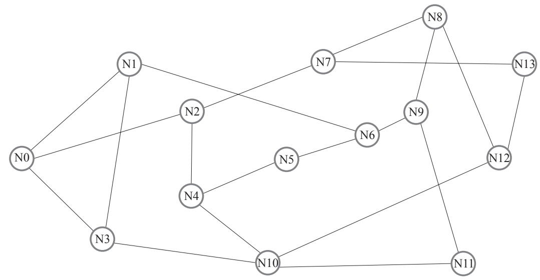


Fig. 7. National Science Foundation network consisting of 14 nodes.

TABLE III
TRADE-OFFS FOR DIFFERENT WEIGHTS, w_F AND w_L.

Relation	$w_F \ll w_L$	$w_F = w_L$	$w_F \gg w_L$
Num. of Lighttours	79	81	83
Used Transmitters[1]	238	241	249
Used Wavelengths[2]	325	320	301
Max. of Virtual Hops	2	3	4
Num. of Virtual Hops	1435	1524	1637

[1] The total number of transmitters is 400 (20 per WRS).
[2] The total number of wavelengths is 400 (20 per fiber).

Another interesting metric concerns the number of OEO conversions. Fixing the amount of resources, while the ILP model solution routes 90% of the traffic using single-hop routing (see Table II), the heuristic routes 63.7% using single hop and 7% using multi-hop. This means that $71\% = \frac{63.7\%}{90\%}$ of the traffic routed with the ILP model using single-hop can also be routed using the heuristic.

B. Shifting Weights

In this subsection we focus on the trade-offs brought on by the weights w_F and w_L in the heuristic. Henceforth, a new topology is considered: the National Science Foundation network (see Fig. 7). For this topology, each wavelength has a capacity of OC-48.

The demand parameters follow the same type of distribution as those described in §V. The total demanded traffic is equivalent to OC-3399. In this case, every WRS has 20 transmitters and receivers available and every fiber can be demultiplexed in 20 wavelengths. The relationship between the weights is set to either $w_F = 1000 \times w_L$, $w_F = w_L$, or $w_L = 1000 \times w_F$.

As expected, the heuristic achieves the maximum possible throughput in the network regardless the values of the weights, but at a different cost. Table III shows this trade-off: three solutions with the same throughput are obtained with different weights. All solutions routed all demands.

By setting $w_F \ll w_L$ (first data column in Table III) the heuristic uses 11 transmitters less and 4 receivers (or lighttours) less in total than when $w_F \gg w_L$ (third data column in Table III). However, the former's price is to use 24 demultiplexed wavelengths more than the later solution. Clearly, if $w_F \gg w_L$, the lighttours would be shorter and, hence, traffic would incur in more OEO conversions, as reflected in the last 2 columns in the table.

Taking this trade-off into account,it can be concluded that $w_F \gg w_L$ is suitable for dynamic networks in which new connections are set and torn down quickly: since lighttours

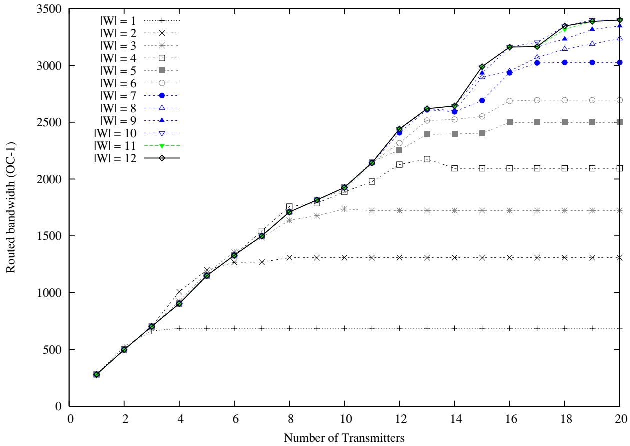


Fig. 8. Throughput of G^+ computed by the heuristic.

are shorter, it offers a high connectivity degree in the virtual network topology. On the contrary, $w_F \ll w_L$ is best suitable for static networks where optimal resource utilization and quality of service provisioning is highly desirable.

C. On Throughput

Although the relationship between w_F and w_L is meaningless for the throughput, the number of transmitters and wavelengths is not. In fact, they affect throughput at different scales as discussed next.

Fig. 8 shows the growth in throughput when the number of transmitters/receivers and wavelengths are varied. Each one of the 12 plots correspond to a set of simulations having the same number of available wavelengths.

The simulation results show that the throughput growth is nearly linear with regards to the number of available transmitters in the network. The rate is approximately OC-164 per transmitter added to every WRS. This means that every WRS is able to route a set of demands equivalent to OC-11.7 each time a transmitter is added to it.

Even though the growth rate is linear in term of the number of transmitters, the growth rate becomes logarithmic in terms of the number of wavelengths. Although a proper plot is not presented, this fact can be seen in the separation between the points when the number of available transmitters per node is 20. The separation becomes smaller as the number of wavelengths increases.

As expected, a better throughput is obtained in G^+ by increasing the number of transmitters than by increasing the number of wavelengths per fiber. Therefore, it can be said that G^+ takes better advantage of the available transmitters in the network, keeping in mind that transmitters/receivers are the major capital expenditure in wavelength-routed networks.

VIII. Conclusions

In this article, a new WRS architecture, named G^+, is proposed. G^+ allows the setup of an optical route that may gather information from many sources while en route towards the destination, therefore reducing OEO conversions. These new optical routes are called *lighttours*.

G^+ is a hybrid architecture of RingO and WDM switching. A WRS in G^+ includes a simple optical device, named λ-monitor device, that enables the routing through lighttours.

To compare G^+ and classical grooming, an ILP model was proposed for solving the GRWA problem considering several objective functions. The ILP model is solved in different scenarios with the objective of reducing the number of OEO conversions to route a given traffic demand matrix.

Using G^+, a reduction of 50% in the number of OEO conversions is achieved. Moreover, maximizing throughput in the model shows that lighttours can offer 20% more throughput that lightpaths using single-hop routing.

A polynomial-time heuristic was proposed as well. The heuristic results are compared with those of the ILP model. Simulation results show that for 70% of the demands, the heuristic results used a few more optical resources than the optimal solution.

An additional set of simulations were performed to analyze the behavior of G^+ in larger networks, which showed that the throughput grows linearly with the number of transmitters and logarithmically with the number of wavelengths.

Future research includes to study synchronization issues, quality of service and scheduling, the network dimensioning problem, dynamic reconfiguration of lighttours, protection, multipath routing.

Acknowledgment

The authors would like to thank Professor Timothy P. Kurzweg, Drexel University, for his comments and insights related to physical optics.

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