Virtual Topology Design of Multiservice Optical Networks

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Abstract – **Wavelength division multiplexing is the most effective way to take advantage of the huge transmission bandwidth provided by the optical media, but the possibility of increasing transmission speed by sharing the same physical link with many optical channels is not the only feature allowed by this technology. Wavelength division multiplexing can also be used to route traffic transparently through some network nodes, thus requiring less electronic data processing at intermediate nodes of a certain traffic route. In such a wavelength-routed network, the traffic is routed through a virtual topology, composed by concatenated ligthpaths embedded in the physical topology of fiber links. This work proposes a new approach to the virtual topology design problem in the core of the Mixed-Integer Linear Program formulation, suitable for a multiservice optical networks. This new formulation allows traffic partitioning in classes and differentiated delay constraining for each traffic class, providing an analysis of its influence on congestion.**

I. Introduction

THE enormous increase of bandwidth demand in the last decade leads to the development of new paradigms for traffic management in high-speed telecommunication networks [1] [2] [3]. In such networks, the optical media has been largely used due to its low attenuation, large bandwidth and transparency. Optical amplification and wavelength division multiplexing (WDM) enhanced even more the capabilities of optical networks.

In former link-based optical networks, all the traffic received by a node is processed in the electrical domain to be routed to the appropriate output port [5]. In this case, wavelength division multiplexing is used only to increase the capacity of the optical fiber links. Indeed, the great transmission bandwidth provided by WDM and other resources, transferred the bottleneck of networks from the transmission media to the nodes, since nowadays data transmission speed in a single optical channel can overcome the electronic data processing limit of the network nodes [4].

Presently, the key note is to minimize electronic signal processing in the network nodes, instead of simply provide more and more bandwidth to the optical channels [4]. Wavelength division multiplexing can be used to route traffic transparently through the network nodes, therefore requiring less electronic data processing [6]. In wavelength-routed networks, the traffic is routed through a virtual topology, composed by ligthpaths, embedded in the physical topology of fiber links [5]. Ligthpaths can be setup between nodes without direct fiber links in between, meaning that a given traffic stream can bypass some intermediate nodes from source to destination, remaining in the optical domain.

II. Logical Topology Design Model

Virtual topology design for wavelength-routed networks has been extensively studied since the middle of the last decade [1] [6]. The optimization of the virtual topology is normally treated as a Mixed-Integer Linear Programming problem (MILP), which becomes intractable for a network with considerable number of nodes. For large networks, heuristic methods [1] [5] [6] are important tools to provide simpler and near-optimal solutions .

The MILP formulation to virtual topology optimization is often applied to circuit-switched optical networks, resulting in a static virtual topology [1] [6]. In this work, the virtual topology is designed to minimize congestion, which is the amount of traffic carried by the most loaded ligthpath, seeking an uniform distribution of traffic between the lightpaths. An end-to-end route for a given traffic demand between two nodes is formed by one or more concatenated ligthpaths. The main constraints to lightpath setup relate to the delay of the traffic in the route between source and destination.

Quality of service (QoS) provisioning is an important issue nowadays, and new protocols [2] are being developed to guarantee appropriate QoS levels for distinct types of services offered through high-speed networks. The discussion of QoS provisioning in multiservice networks [7] often starts from a common point: the traffic is heterogeneous regarding to its QoS requirements [4]. The QoS level to be guaranteed depends upon the nature of the service, and not by the traffic itself, e. g. , real-time voice streaming needs a higher QoS level than e-mail transmission, for obvious reasons. QoS provisioning in multiservice networks requires traffic classification according to its QoS requirements, and the data packets associated with each of these traffic classes must occupy network resources with the appropriate priority level [7].

This work presents an original MILP formulation to design virtual topologies of wavelength-routed multiservice networks. The proposed formulation deals with multiple classes of traffic and different routing criteria to each class. The traffic class with higher priority of transmission is routed with very tight delay constraining, and, as the priority decreases for the other classes, these constraints are relaxed gradually. The objective of the multiple class formulation is to offer priority in the shortest routes (tighter delay constraints) to the traffic class with higher QoS demand in a multiservice optical network.

The MILP formulation proposed in this work has two primary inputs: the physical topology matrix *D* and the traffic matrix Λ, specifying the traffic demands $\Lambda(s,d,c)$ between the source (*s*) and destination (*d*) nodes for each one of the three traffic classes *c* = 1, 2, 3.

Ligthpaths are setup between pairs of nodes *(i,j)*, through one or more fiber links. A given traffic demand $\Lambda(s,d,c)$ is transmitted from *s* to *d* through one or more concatenated ligthpaths. The amount of traffic carried by a certain ligthpath between *(i,j)* that is part of the demand $\Lambda(s,d,c)$ is called traffic component of $\Lambda(s,d,c)$ and is represented by $\lambda(i,j,s,d,c)$. The amount of traffic of a given class *c*, transmitted through the ligthpath between *(i,j)*, is $\lambda(i,j,c)$, and the entire traffic load of this ligthpath is $\lambda(i,j)$. The number of ligthpaths that can be setup from or to a given node of the network is called logical degree, represented by Δ_l.

Delay constraints are built upon the physical topology matrix, since the propagation delay *D(i,j)* between a pair of nodes *(i,j)* is considered proportional to the physical length of the shortest physical route between these nodes [1] [6], in a manner that each traffic component $\lambda(i,j,s,d,c)$ has a propagation delay *D(i,j)*. The results are the achieved congestion λ_{max} and the virtual topology matrix *B*. The elements *B(i,j)* of the virtual topology matrix are binary variables, which indicate whether (*B(i,j)* = 1) or not (*B(i,j)* = 0) a ligthpath is setup between the pair of nodes *(i,j)*. Congestion λ_{max} is the amount of traffic carried by the ligthpath with the highest load. Under these definitions, the MILP formulation is stated:

a) Objective function

$$\text{Minimize } (\lambda_{\max}) \qquad (1)$$

b) Congestion definition

$$\lambda(i,j) \le \lambda_{\max} \qquad (2)$$

c) Traffic flow conservation

$$\sum_j \lambda(i,j,s,d,c) - \sum_j \lambda(i,j,s,d,c) = \begin{cases} \Lambda(s,d,c); s = i \\ -\Lambda(s,d,c); d = i \\ 0; s \ne i, d \ne i \end{cases} \qquad (3)$$

$$, \forall(s,d,c)$$

$$\lambda(i,j,c) = \sum_{s,d} \lambda(i,j,s,d,c), \forall(i,j,c) \qquad (4)$$

$$\lambda(i,j) = \sum_c \lambda(i,j,c), \forall(i,j) \qquad (5)$$

$$\lambda(i,j,s,d,c) \le B(i,j).\Lambda(s,d,c) \qquad (6)$$

d) Delay constraints

$$\sum_{i,j} \lambda(i,j,s,d,c).d(i,j) \le \Lambda(s,d,c)\alpha_c.d_{\max} \qquad (7)$$

e) Logical degree constraints

$$\sum_i B(i,j) = \Delta_l; \forall j \qquad (8)$$

$$\sum_j B(i,j) = \Delta_l; \forall i \qquad (9)$$

Traffic flow conservation constraints given by Eq. (2) guarantees that the sum of traffic components of a given class *c* coming from the source node *s* is equal to the amount of traffic arriving at the destination node *d*, and also equals to the traffic demand $\Lambda(s,d,c)$. At the intermediate nodes *(i,j)* in the route from *s* to *d*, *(i,j)* ≠ *(s,d)*, the sum of the components $\lambda(i,j,s,d,c)$ of $\Lambda(s,d,c)$ is zero.

Equations (3) and (4) state the relationship between the traffic components $\lambda(i,j,s,d,c)$, the traffic of a class *c* $\lambda(i,j,c)$, and the entire traffic of a ligthpath $\lambda(i,j)$. The last constraints of this group, given by Eq. (5) define the dependence of the virtual topology matrix components *B(i,j)* and the traffic components $\lambda(i,j,s,d,c)$, in a manner that the components $\lambda(i,j,s,d,c)$ are non-zero only if *B(i,j)* = 1 (ligthpath from *i* to *j* exists) and do not exceed $\Lambda(s,d,c)$ if *B(i,j)* = 1.

Equation (6) defines congestion, which is the amount of traffic carried by the most loaded ligthpath. The objective function (Eq.(1)) minimizes congestion, seeking the most balanced traffic distribution between all the ligthpaths.

The group of constraints that are different for each traffic class are the delay constraints of Eq. (7). The delay bound is on the left side of the delay constraints, given by Eq. (10) below,

$$\alpha_c.d_{\max} \qquad (10)$$

where d_{max} is the delay of the longest route in the set of shortest routes between all *(s,d)* pairs. This delay bound is equal for all constraints (homogeneous delay constraining) and was adopted to permit comparison with previous works [1] [6]. The parameter α_c is a delay relaxation factor applied over d_{max}, in a manner that as higher α_c is, less restricted is the routing of the traffic assigned to the class *c* (differentiated delay constraining).

The case of study will be the six-node network with physical topology depicted in Fig. 1. This example was taken from [6] and permits some basic comparison to validate the optimization and constraint synthesis procedures.

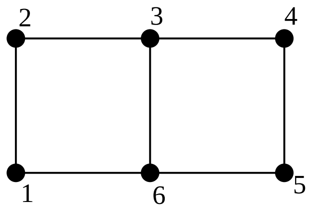

Fig. 1: Physical topology of the six-network (not on scale).

The traffic matrix (Table 1) shows the traffic demands between each pair *(s,d)* of the network of Fig. 1, disregarding any traffic partitioning, as mentioned before. The distance matrix (Table 2) specify the physical length of the fiber links between the nodes, depicted in Fig. 1.

TABLE I

SINGLE CLASS TRAFFIC MATRIX $\Lambda(s,d)$ – NETWORK OF FIG. 1

s						
	-	0.537	0.524	0.710	0.803	0.974
	0.391	-	0.203	0.234	0.141	0.831
	0.060	0.453	-	0.645	0.204	0.106
	0.508	0.660	0.494	-	0.426	0.682
	0.480	0.174	0.522	0.879	-	0.241
	0.950	0.406	0.175	0.656	0.193	-

TABLE 2

DISTANCE MATRIX *D(I,J)* – NETWORK OF FIG. 1

i						
	-	800	-	-	-	1000
	800	-	1500	-	-	-
	-	1500	-	1000	-	600
	-	-	1000	-	500	-
	-	-	-	500	-	1500
	1000	-	600	-	1500	-

III. SINGLE CLASS VIRTUAL TOPOLOGY DESIGN: UNIFORM DELAY CONSTRAINING

In this section, the MILP formulation does not consider traffic partitioning, as done in [1] [6]. This case has a single class of traffic, meaning that the entire traffic will be routed with the same delay relaxation factor α.

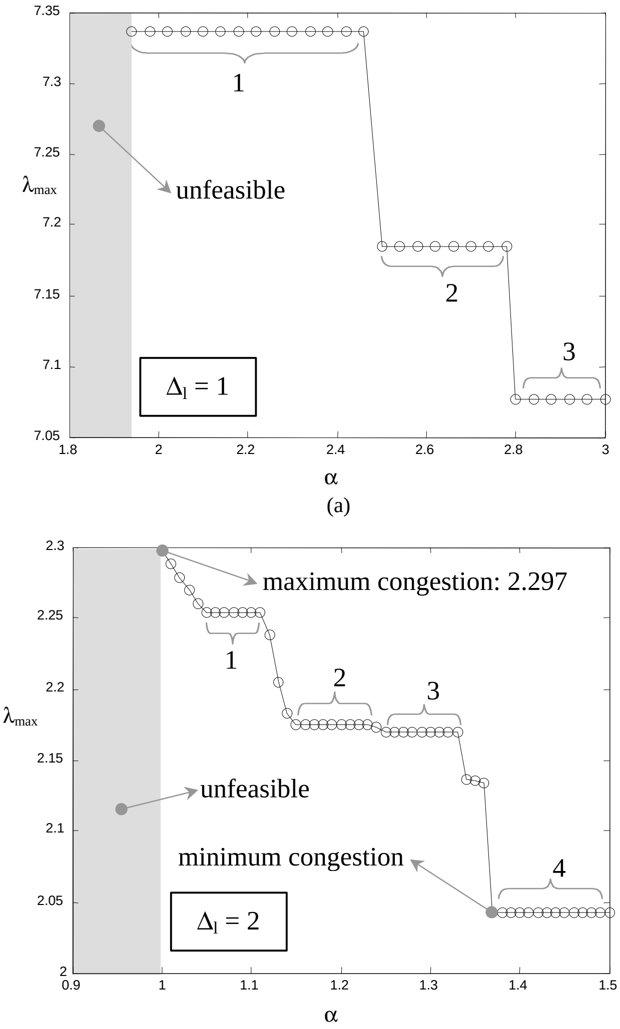

Fig 2: Optimal congestion (λ_{max}) values (circles) obtained varying α, for a logical degree (a) Δ_l = 1 and (b) Δ_l = 2, and no traffic partitioning (*c* = 1).

The results for congestion obtained for different delay relaxation factors α and logical degrees, Δ_l = 1 and 2, are shown in Fig. 2(a) and 2(b), respectively, leading to some remarks:

a) no feasible virtual topology is possible in the shaded regions: α < 1.933 in Fig. 2(a) and α < 1 in Fig. 2(b);

b) congestion changes abruptly between three values in Fig. 2a; a smoother curve was obtained in Fig. 2b;

c) congestion remains stable in the regions marked with braces and numbered in Figs. 2 (a) and (b). The virtual topologies obtained for these values of l_{max} will be called stable virtual topologies, regarding delay constraining.

d) the difference between the maximum and the minimum values of congestion is the congestion range, given D_l.

The exact values of congestion of the stable virtual topologies (Fig. 2) are shown in Table 3.

TABLE 3

ACHIEVED CONGESTION FOR THE STABLE VIRTUAL TOPOLOGIES

Δ		
io	α	λ
s	α < 1.933	-
	1.933 < α < 2.5	7.336
	2.5 ≤ α < 2.8	7.185
	α ≥ 2.8	7.077
Δ		
io	α	λ
s	α < 1	-
	1.05 ≤ α < 1.12	2.254
	1.15 ≤ α < 1.24	2.175
	1.25 ≤ α < 1.34	2.170
	α ≥ 1.37	2.042

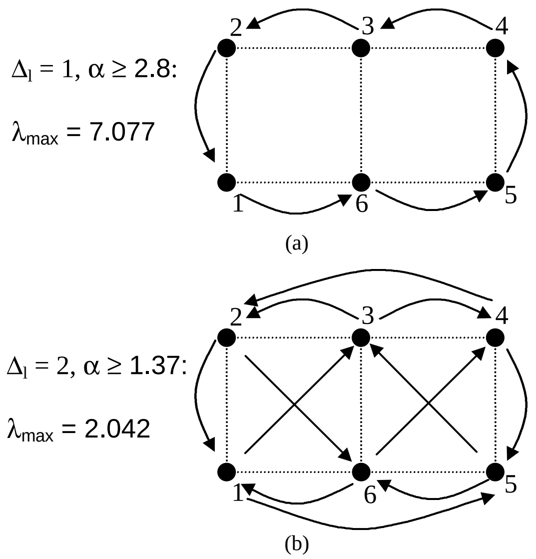

Fig. 3: Optimal virtual topologies obtained for logical degree (a) D_l = 1, α ≥ 2.8 and (b) D_l = 2, a ≥ 1.37, resulting in the minimum achievable congestion for each case ((a) l_{max} = 7.077; (b) l_{max} = 2.042).

The optimal virtual topologies for the minimum achievable congestion are shown in Fig. 3(a) and (b), respectively for D_l = 1 and 2.

The number of lightpaths in the virtual topology with D_l = 2 is higher than the obtained for D_l = 1 (Fig. 3), resulting in more possibilities of alternate paths between a pair of nodes *(s,d)*, increasing the flexibility to route the traffic components l *(i,j,s,d,c)* of a given demand L*(s,d,c)* through the network. The flexibility provided by D_l = 2 is responsible for the smoother congestion curve in Fig. 2(b), where up to two ligthpaths can be set at each node, allowing more optimal solutions for the MILP varying α. The virtual topologies obtained for D_l = 1 (Fig. 3(a)) are always ring-fashioned, with no possibilities of multiple paths between a given pair of nodes *(i,j)*.

These are the results obtained for *c* = 1, which means no traffic partitioning and uniform delay constraining. In the next section, the traffic demands of Table 1 (traffic matrix) will be partitioned and differentiated delay constraining will be applied to each traffic class (*c* = 1,2,3).

III. MULTIPLE CLASSES VIRTUAL TOPOLOGY DESIGN: DIFFERENTIATED DELAY CONSTRAINING

A. Impact on Congestion

It is expected that traffic partitioning in classes associated with differentiated delay constraining will increase the flexibility of virtual topology optimization problem, when compared with the single class case, resulting in lower values of congestion.

Traffic class 3 will not be delay bounded ($a_3 \rightarrow \infty$) and the tightest delay constraining will be applied to class 1 ($a_1 < a_2 < a_3$). The proportion of traffic and the delay relaxation factors a_c (*c* = 1,2,3) assigned to each traffic class will determine congestion.

The traffic matrix for each class is given by Eq. (11), where P_c is the proportion [%] of the traffic assigned to class *c*, following the condition given by Eq. (12).

$$\Lambda(s,d,c) = \Lambda(s,d).\frac{P_c[\%]}{100} \qquad (11)$$

$$\sum_{c=1}^{3} \frac{P_c}{100} = 1 \qquad (12)$$

Two cases of differentiated delay constraining for D_l = 2 are analyzed (Table 4), and the results for several traffic distributions, represented by [P_1, P_2, P_3], are shown in Fig. 4.

TABLE 4

VALUES OF α_C (C = 1, 2, 3) ADOPTED IN MULTIPLE CLASSES VIRTUAL TOPOLOGY OPTIMIZATION WITH DIFFERENTIATED DELAY CONSTRAINING

Δ			
s	α	α	α
A	1.1	1.2	∞
B	1.1	1.3	∞

The comparison between the single and multiple classes approaches can be done with the result in the point [P_1,P_2,P_3] = [100%,0%,0%] (λ_{max} = 2.254) of Fig. 4, which is equivalent to a single class condition, because no traffic is assigned to the classes 2 and 3. The results of Fig. 4 show that congestion decreases if the amount of traffic assigned to class 1 is reduced. The lowest value for congestion in Fig. 4 (λ_{max} = 2.175) is reached around [P_1,P_2,P_3] = [60%,25%,15%] and [70%,20%,10%] for cases (A) and (B) respectively (Table 4). No further congestion decrease was observed for $P_1 > 0$.

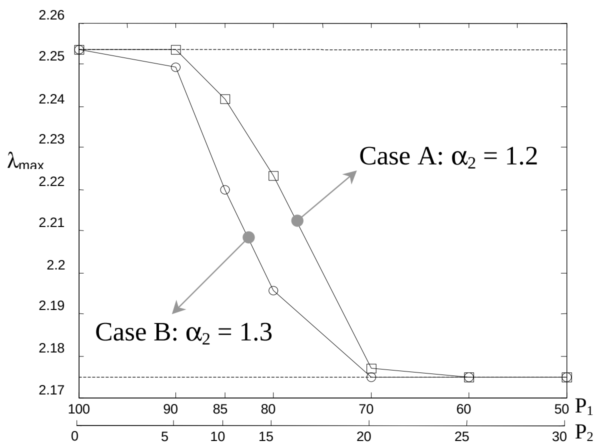

Fig. 4: Optimal congestion (λ_{max}) values for two cases (A – squares and B – circles) of differentiated delay constraining (Table 4) with traffic partitioning in three classes ($P_1 + P_2 + P_3$ = 100%), for the proposed six-node network with Δ_l = 2.

The gradual redistribution of traffic from class 1 to the other two less restricted classes 2 and 3 caused a significant congestion reduction, as seen in Fig. 4. The lowest achievable congestion is given by the traffic distribution [P_1,P_2,P_3] = [0%,0%,100%] (no delay constraining: $\alpha_3 \rightarrow \infty$), resulting in λ_{max} = 2.042 (Fig. 2(b)). It defines a maximum achievable congestion reduction of $\Delta\lambda_{max}$ = 0.212 for cases (A) and (B). The congestion decrease obtained for $P_1 > 0$ is equivalent to 37% of the defined maximum achievable congestion reduction.

The difference in congestion between the two cases shown in Fig. 4 is considerable in the range [90%,5%,5%] < [P_1,P_2,P_3] < [70%,20%,10%]. A less restricted delay constraining for the intermediate class (α_2 = 1.3), resulted in lower values for congestion in this range, but both cases converge to the same congestion value at the point [P_1,P_2,P_3] = [60%,25%,15%].

B. Traffic Component Distribution

The same lightpath configuration can be obtained for single and multiple classes approaches, with different traffic component distribution. For example, the ligthpath topology obtained for case (B) (Table 4) with [P_1,P_2,P_3] = [70%,20%,10%] (λ_{max} = 2.175 – Fig. 4), depicted in Fig. 5, is identical to the obtained for the single class approach with Δ_l = 2 and α = 1.2 (λ_{max} = 2.175 – Tab 3).

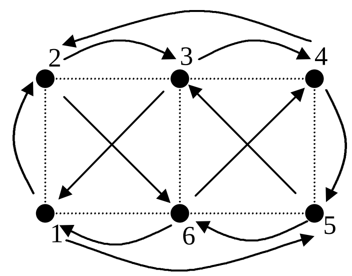

Fig. 5: Optimal virtual topology for both single class (α = 1.2) and multiple classes (α_1 = 1.1, α_2 = 1.3, $\alpha_3 \rightarrow \infty$; [$P_1$,$P_2$,$P_3$] = [70%,20%]) formulations with Δ_l = 2, resulting in λ_{max} = 2.175.

Using the multiple class approach, it is possible to route 70% of the network traffic with α = 1.1 and λ_{max} = 2.175 in the ligthpath topology of Fig. 5. On the other hand, with the single class approach, the traffic has to be routed with more relaxed delay constraining to achieve the same value of congestion with this ligthpath topology. This is accomplished due to the more efficient traffic component distribution in the multiple class case. For example, Table 5 shows how the components of the traffic demand $\Lambda(1,4)$ = 0.710 are distributed between source (s = 1) and destination (d = 4) in the lightpath configuration of Fig. 5, for single and multiple classes formulations.

Table 5 shows how the traffic demand $\Lambda(1,4)$ is delivered through different routes in the single and multiple classes approaches. For example, in the multiple class case, the portion of traffic assigned to class 1 (P_1 = 70%; α_1 = 1.1) of the demand $\Lambda(1,4)$, is routed in a single path composed by the lightpaths 1→2, 2→3 and 3→4 (route 1), carrying the traffic components $\lambda(1,2,1,4,1)$, $\lambda(2,3,1,4,1)$ and $\lambda(3,4,1,4,1)$ respectively. The delay of each route is also specified.

TABLE 5

DISTRIBUTION OF Λ(1,4) TRAFFIC COMPONENTS FOR SINGLE (α = 1.2) AND MULTIPLE CLASSES (CASE (B), [P1,P2,P3] = [70%,20%,10%])

i ss Δ				
ss	α	**o**	**i h hs**	
	1.2	1	1→2, 2→3, 3→4	3300
	1.2	2	1→5, 5→3, 3→4	5000
i ss s Δ				
ss	α	**o**	**i h hs**	
	1.1	1	1→2, 2→3, 3→4	3300
	1.3	1	1→2, 2→3, 3→4	3300
	1.3	3	1→2, 2→6, 6→4	4200
	∞	4	1→5, 6→4, 5→6	5500

The greater flexibility in traffic component distribution provided by the multiple classes approach can be observed in Table 5. Dividing the traffic demand L*(1,4)* in three classes ($[P_1,P_2,P_3]$ = [70%,20%,10%]), three different routes (1, 3 and 4) are possible, instead of two, in the single class case. The higher number of alternate routes is the principal cause of the better traffic balance obtained in the multiple classes case.

IV. CONCLUSION

A new method for virtual topology design was presented in this work, suitable for multiservice networks. Designing virtual topologies with mutiple traffic classes allows the application of different delay constraining to each class, defining levels of priority in the contention of the shortest routes. Consequently, the traffic component distribution is different for the multiple and the single class approaches, even with the same lightpath topology and congestion. The main advantage of the multiple class approach consists that a significant amount of traffic is routed with tighter delay constraining than in the single class approach.

The higher efficiency achieved with the multiple class model is also observed when the traffic is distributed from the class with tightest delay constraining to the other classes. A significant congestion decrease is obtained with just 20% of the traffic being assigned to class 2 and 10% to class 3.

Another important conclusion adresses the greater flexibility achieved with traffic component routing in the multiple class approach, where each traffic class can be routed through a different route. This is possible because the traffic components are distinct for each class, allowing different routing solutions. In the single class case, the logical degree constraints impose a more severe restriction in the number of routing possibilities for the traffic components, since the lightpaths can carry only one component of a given traffic demand.

Further studies are being pursued to impose restrictions on the number of hops. The intention is to associate traffic classes with delay-sensitive applications. Heuristic-based approaches are being developed to design virtual topologies for larger size multiservice optical networks.

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