Forwarding Adjacencies (FA) by the routing protocol in the upper layer.

In this paper we concentrate on the off-line dimensioning of layouts. Many offline algorithms to optimize virtual layouts according to different criteria such as delay or maximum throughput have already been proposed (see for example [2] – [4]). Previous studies [2], [5] have also already focused on lightening the work of the operator by reducing the complexity of the layout; this has been done mainly by minimizing the number of LSPs. Indeed, the OPEX for an operator is an increasing function of the number of LSPs which have to be controlled, monitored and maintained. Even in coordination with online heuristics such as the one described in [6], having an offline algorithm is most useful, as it provides the initial necessary optimal solution corresponding to an average point of operation. This initial solution is often needed for the online algorithm to operate slight changes around it.

In a GMPLS context, unidirectional bus-LSPs[2] seem a natural idea to introduce for the purpose of simplifying the network layout. A unidirectional bus-LSP is defined in this paper (see Section 2) as an LSP on which intermediate nodes may add or drop packets. For example, in an IP over WDM network, the bus-LSP can be composed of a unique optical (lambda) connection between an ingress and an egress equipment with all equipment in the path having the possibility of add/dropping packets into/from this connection. In [4], the authors use the possibility of adding traffic onto an LSP at an intermediate node in an all-optical transparent network to improve throughput and reduce network cost. However, we will show here that in a routed environment, this throughput increase and cost reduction can be achieved by using the nesting technique, at the cost of router processing load.

The main contribution of this paper is the evaluation of the bus-LSPs. We show how they can be used to reduce CAPEX and OPEX of a multilayer network. Concerning the CAPEX, we show that resources (like bandwidth and switching capacity) and components (like interfaces and electro-optical converters) can be saved. Concerning the OPEX, we show that bus-LSPs allow reducing the layout complexity measured by the number of LSPs that have to be established and maintained. For this purpose, we propose a realistic network model, based on which we compare the cost of optimal designs for the cases where bus-LSPs are allowed and not allowed.

The rest of the paper is structured as follows. We first introduce the bus-LSP concept in Section 2 and show how the concept can be used to reduce CAPEX. In Section 3 we define the network model we propose for the layout optimization. The detailed optimization problem formulation is presented in Section 4. Two complementary formulations are made: the first one relates to the optimization of the total number of bus-LSPs regardless of the total bandwidth used in the network, whereas the second will minimize the total number of bus-LSPs while using a minimal amount of total bandwidth. The two problem formulations are numerically studied under various traffic conditions in Section 5. Finally, in Section 6 conclusions are drawn and future work is presented.

2. THE UNIDIRECTIONAL BUS-LSP

In a GMPLS-controlled multilayer network, a Label Switched Path (LSP) is a connection between ingress and egress LSRs (Label Switching Routers), spanning one or more links. The

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[2] The feasibility of this concept in the optical LSPs case has been proven by manufacturers.

links can be physical links such as fibers, or lower-layer LSPs nesting the LSP, as long as the hierarchy defined in [7] is respected. A Forwarding Adjacency (FA) is a representation, at the Control Plane, of the connectivity that one or several LSP offer in the data plane between the ingress and egress. It can therefore be used in upper layers as a physical link is used by the bottom layer.

What we call here bus-LSP and bus-FA are extensions of these concepts of LSP and FA. On a bus-LSP, intermediate LSRs in the LSP have the possibility of adding and dropping data on the bus-LSP. We will call these nodes add-drop points. A bus-LSP provides a forwarding connectivity between ingress, add-drop points and egress in the data plane. We call the representation of this connectivity in the Control Plane a bus-FA. A mechanism allows the ingress of the bus-FA and any add point to specify which single node on the bus-FA the data sent is addressed to. This solution is neither a multicast one nor a multipoint-to-(multi) point one. In the present paper, and for the feasibility of the implementation, the bus-LSP supporting the bus-FA is unidirectional. Hence, data may only be sent to a drop point (or the egress) which is downstream from the sending add point (or ingress).

The bus-LSP concept allows reducing the number of LSPs to be setup and therefore the operation and maintenance costs. We quantified the gain for two examples in Sections 4 and 5.

However, this is not the only benefit of bus-LSPs, as shown hereafter. We analyze two cases. In the first one we consider a network of just two layers, the physical network layer and a second one allowing the deployment of a layout that will support directly the traffic. There is no routing over the layout allowing the transport of traffic over more than one FA (we call the corresponding network architecture "non-routed architecture"). In the second case, there is third layer that can route the traffic over several FAs (there is no need here for a full mesh).

2.1. Benefits of the Bus-LSP in Non-Routed Architectures

In a direct point to point architecture (see Figure 1), each traffic demand between two nodes is transported over a single point to point FA between the nodes (no bus-FAs are used). We will call this architecture DP2P (direct point-to-point). In the following we consider that the FAs are supported by lambda connections.

As an example, let us consider a physical topology composed of three nodes A,B and C

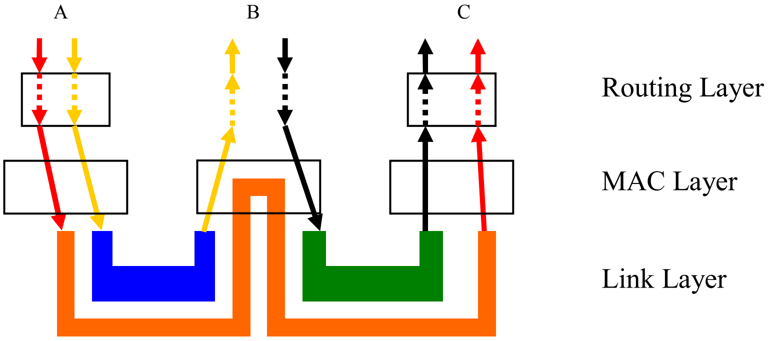

Figure 1. Direct Point to Point Architecture

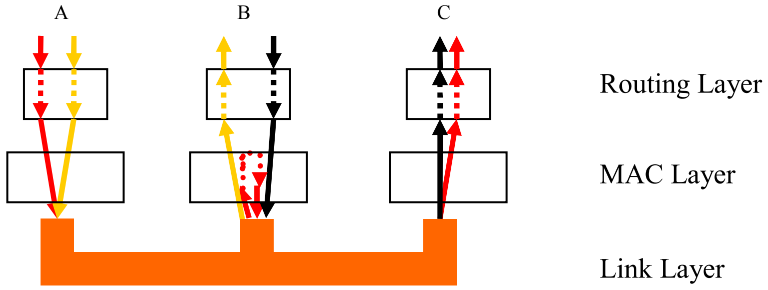

Figure 2. Bus-LSP Architecture

which are connected by two links, one from A to B and the other from B to C (as shown in Figures 1 and 2). When comparing the DP2P solution with the bus-LSP one represented in Figure 2, we observe that:

1- The DP2P approach requires maintaining two LSPs on each link, instead of only one for the bus-LSP (see Figure 2).

2- Because of the discrete bandwidth of lambda connections, no statistical multiplexing is allowed in the DP2P case between the A to B and A to C traffic, neither between the A to C and B to C traffic. Therefore, more resources are usually consumed. This idea has been partially explored in [4] using a more restrictive, yet related to the bus-LSP, technology.

3- Twice as many wavelengths and total opto-electronic converters as required.

The DP2P is therefore more resource-consuming and implies a greater management complexity since the number of required LSPs is larger. The gain increases with the size of the network.

2.2. Benefits of the Bus-LSP in Routed Architectures

In a multilayer environment, it is possible to route demands over multiple FAs or bus-FAs. We compare here a bus-LSP based architecture to a situation (see Figure 3) where all traffic demands are supported by LSPs which are setup only between physically adjacent nodes that can switch traffic. We will call this situation MH (multi-hopped).

As an example, let us consider the same topology as in the previous section. When comparing the MH solution with the bus-LSP one, we observe that:

1- Where the MH architecture has to setup and maintain two or more LSPs, only one bus-LSP is needed.

2- The bus-LSP structure is less demanding in router resources than the MH structure; indeed, transit packets in a node are not routed at layer 3 but just forwarded at layer 2. This can be done very easily if layer 2 frames are tagged with a mark indicating the corresponding dropping node. This means a lighter load for the router, and processing power is spared, which can directly be converted to cost reduction for the operator.

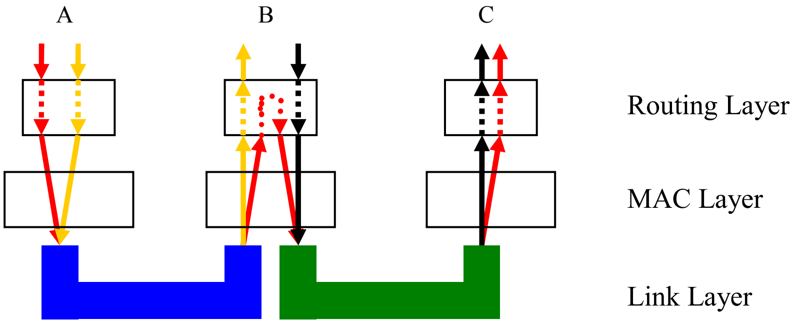

Figure 3. Multi-Hopped Architecture

3- If the layer 3 routing function is provided by a separate equipment, the bus-LSP will save resources at the interface between layer 3 and lower layers equipment, this can even reduce the number of required physical interfaces in big networks.

4- Finally, the bus-LSP and MH architectures are strictly equivalent in terms of statistical multiplexing since both can multiplex multiple flows onto a single LSP.

2.3. Signaling and Routing Requirements

The unidirectional bus-LSP being a novel concept in the GMPLS domain, most specific procedures have to be defined for using them in existing GMPLS networks. A bus-LSP is setup using the same type of RSVP-TE [8], [9] mechanisms as for establishing a regular LSP. However, signaling extensions have to be defined to setup, modify, delete, protect and restore these particular LSPs. The solution has to be transparent to non bus-LSP aware nodes. We have specified these signaling extensions; the outcome of this work will be submitted in a separate paper. Similarly, an extension to the routing protocol, namely OSPF-TE [10], has to be designed for representing bus-FAs as part of routing information, and distributing the corresponding data like routing metrics.

3. OPTIMIZATION MODEL FOR A NETWORK USING BUS-LSPs

In the following sections we will quantitatively analyze the benefits of bus-LSPs in terms layout complexity reduction. In the present section we introduce a two layer (non-routed) network model and the various related notations that we use in following sections.

3.1. Network and Paths

The physical network is represented by a directed graph $G = (V,A)$, where V is the set of vertices indexed by the general subscript $n=1..N$, and A is the set of edges indexed by the general subscript $e=1..E$. The vertices represent here the GMPLS Label Switching Routers (LSRs) and each edge represents a unidirectional connecting link between them. Additionally, we denote by c_e the nominal capacity of link e.

Since our target is to show the benefits of bus-LSPs in terms of reduction of the number of objects to be set-up and maintained, a path formulation of the network optimization problem is better adapted than a node-link formulation. Let the general subscript $p=1..P$ index all considered paths in the network. Note of course that in practical cases, the network operator can select the list of paths that can be used; this is taken into account in our model. A path is characterized by the ordered succession of links it uses. In the bus-LSP context, a path and a bus-LSP will be considered as equivalent, that is, all nodes along a path will be able to add or remove packets on the bus. We suppose in this paper that bus-LSPs don't cross a given router more than once.

3.2. Demands and Flows

Let the general subscript $d=1..$D index all network demands, that is the various end-to-end commodities. Demand d requires bandwidth h_d.

Since we consider a non-routed architecture, demands have to use a single (bus-)FA to go from source to destination.

Let δ_{edp} be the binary variable that takes the value "1" when path (or bus-LSP) p requires bandwidth on link e when satisfying demand d, and the value "0" otherwise. We assume here that the signaling and routing protocols allow for the residual bandwidth to vary along a given bus-LSP, depending on the initial nominal capacities of the links composing the bus-LSP and the bandwidth reservations made on each segment of the bus-LSP.

Let γ_{dp} be the binary variable indicating if path (or bus-LSP) p can effectively transport demand d. Again, the operator can restrict the usage of a path for the transport of a given flow so as to guarantee delay constraints for example.

Let x_{dp} be the continuous variable indicating how much flow from demand d is routed on path p.

Let u_p be the binary variable associated with path p indicating whether path p is activated or not.

4. OPTIMIZATION PROBLEMS FORMULATIONS

Given the physical network configuration and a traffic matrix, the objective here is to minimize the total number of LSPs a network operator has to manage. We formulate two problems with this in mind: the first consists in minimizing the number of active LSPs with the constraints of transporting all the traffic without overloading any link and the second has the additional target of keeping the overall bandwidth consumption minimal.

4.1. Reduced Complexity Layout With Bus-LSPs

The operational expense for a network operator is related to the layout complexity. In this paper, we define complexity as the total number of LSPs which are simultaneously active. We formulate in this section a multi-commodity flow problem with the objective of minimizing this number of bus-LSPs. The MCL (Minimal Complexity Layout) problem is formulated as Mixed Integer Linear Program (MILP), as some of the variables (like the u_p) are integers and other (like the x_{dp}) are continuous.

Problem 1 : MCL- Minimal Complexity Layout

Given:

The sets of links *{1..E}*, of demands *{1..D}* and of paths *{1..P}* as well as:

h_d for $d=1..D$

c_e for $e=1..E$

δ_{edp} for $d=1..D$; $e=1..E$; $p=1..P$ *and*

γ_{dp} for $d=1..D$; $p=1..P$

Minimize:

$$\sum_{p=1}^{P} u_p \tag{1}$$

Subject to:

$$\sum_{d=1}^{D}\sum_{p=1}^{P} \delta_{edp}.x_{dp} \le c_e \qquad , e=1..E \tag{2}$$

$$\sum_{p=1}^{P} x_{dp}.\gamma_{dp} = h_d \qquad , d=1..D \tag{3}$$

$$x_{dp} \le h_d.u_p \qquad , d=1..D, p=1..P \tag{4}$$

Constraint (2) ensures that no link carries more flow than its nominal capacity. Constraint (3) expresses the fact that all the demand is satisfied and only authorized paths are used for each demand. Constraint (4) ensures that there is no flow on inactive bus-LSPs (for which $u_p=0$). We allow here for load-balancing, or flow bifurcation, since we do not impose for a commodity to be satisfied by a single path.

4.2. Reduced Complexity, Minimal Overall Bandwidth Layout With Bus-LSPs

As we will show in the numerical study in Section 5, minimizing the number of bus-LSPs can lead to wasting a lot of bandwidth in the network, as demands may be multiplexed on too long bus-LSPs. Therefore, we propose another formulation, where we have the additional constraint that the overall used bandwidth does not exceed the minimal overall bandwidth required to support the demand in a network that does not implement bus-LSPs.

This MCL-BC (Minimal Complexity Layout with Bandwidth Constraint) problem is solved in two steps. The first one consists in determining the minimal bandwidth utilization (B^*) of a layout not using bus-LSPs. This is obtained by solving a MCL problem similar to the one formulated in Section 4.1 for which only the objective (1) is changed and becomes:

Minimize:

$$\sum_{e=1}^{E}\left(\sum_{p=1}^{P}\sum_{d=1}^{D}\delta_{edp}.x_{dp}\right) \tag{5}$$

This leads to a minimal network utilization B^*. As the u_p variables are no longer constrained, they can all be set to 1, which means that flows can be routed on all paths, and only the ones using a minimal amount of bandwidth will be selected, regardless of how many are used and whether there is load balancing or not. We then use this to solve a variation of the MCL problem with this optimal bandwidth utilization as an additional constraint (10):

Problem 2 : MCL-BC

Given:

The sets of links *{1..E}*, of demands *{1..D}* and of paths *{1..P}* as well as:

h_d for $d=1..D$
c_e for $e=1..E$
δ_{edp} for $d=1..D$; $e=1..E$; $p=1..P$
γ_{dp} for $d=1..D$; $p=1..P$

Minimize:

$$\sum_{p=1}^{P}u_p \tag{6}$$

Subject to:

$$\sum_{d=1}^{D}\sum_{p=1}^{P}\delta_{edp}.x_{dp} \le c_e \qquad , e=1..E \tag{7}$$

$$\sum_{p=1}^{P}x_{dp}.\gamma_{dp} = h_d \qquad , d=1..D \tag{8}$$

$$x_{dp} \le h_d.u_p \qquad , d=1..D, p=1..P \tag{9}$$

$$\sum_{e=1}^{E}\left(\sum_{p=1}^{P}\sum_{d=1}^{D}\delta_{edp}.x_{dp}\right) \le B^* + \Delta \tag{10}$$

where Δ is how close the solution needs to be to the optimal bandwidth use B^*. (6), (7), (8), and (9) are respectively the same as (1), (2), (3) and (4).

4.3. Problem Formulation Improvements and Additional Constraints

An operator might want to ensure that all data associated with a given commodity flows through the same path. This can be imposed in the model by adding a binary variable v_{dp} which is set at 1 if demand *d* uses path *p*; and two constraints:

$$\sum_{p=1}^{P} v_{dp} = 1 \qquad ,d=1..D \tag{11}$$

$$x_{dp} \le h_d . v_{dp} \qquad , d=1..D, p=1..P \tag{12}$$

Constraint (11) guarantees that only one path will be used for a given demand. Constraint (12) ensures that flow will only be assigned to a path which is the path designated for routing the demand.

Another additional constraint one might want to consider is the possibility of weighting bandwidth utilization on the different links, to take into account factors such as length or technology of the link. By introducing an additional cost variable g_e for each link *e*, one may replace (5) by:

<u>Minimize</u>:

$$\sum_{e=1}^{E} (\sum_{p=1}^{P} \sum_{d=1}^{D} \delta_{edp} . g_e . x_{dp}) \tag{5.bis}$$

This new objective (5.bis) will yield a different overall network cost B*', which is used to replace constraint (10) by:

$$\sum_{e=1}^{E} (\sum_{p=1}^{P} \sum_{d=1}^{D} \delta_{edp} . g_e . x_{dp}) \le B^{*} \tag{10.bis}$$

Finally, if the results produced by this algorithm are to produce an average point of operation which will be subject to traffic matrix variations in time, it can be interesting to change constraint (2) and (7) to:

$$\sum_{d=1}^{D} \sum_{p=1}^{P} \delta_{edp} . x_{dp} \le c_e . \theta \qquad , e=1..E, \tag{13}$$

where θ is a coefficient chosen to ensure that no link in the yielded solution will be excessively loaded, leaving thus some margin for traffic variations.

5. NUMERICAL RESULTS

In this section, we present a numerical study of the previous problems (MCL and

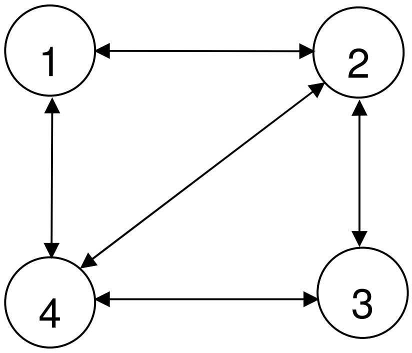

Figure 4. NET1 Network

MCL-BC). We compare the complexity of the layouts when bus-LSPs are allowed and not allowed and show that the bus-LSP allows for drastically reducing this complexity. Since we consider the non routed case, the number of LSPs required in the non-bus LSP case is at least the total number of demands. To simplify the presentation, we compare the number of required bus-LSPs with the total number of demands, which corresponds to a worst case of the gain.

The results are obtained by submitting the formulated problem to the numerical solver ILOG CPLEX. We present results for two networks, noted NET1 and NET2. NET1 (Figure 4)

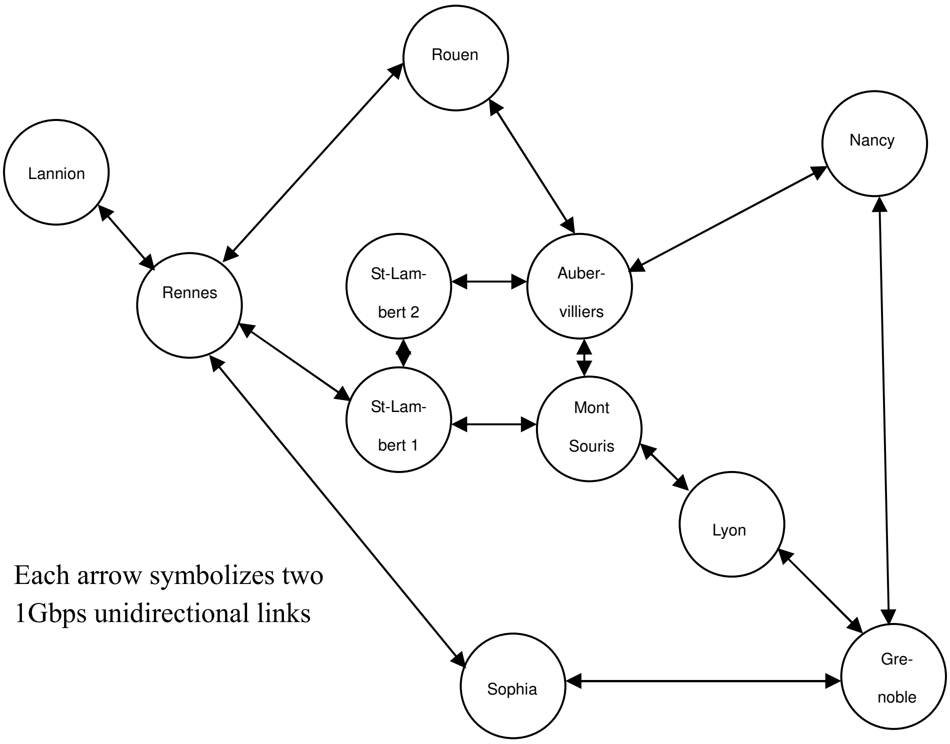

Figure 5. NET2 Network

is a 4 node network, with 10 unidirectional links (this very simple network topology allows to develop some intuition on the benefits of bus-LSPs). NET2 (Figure 5) is an 11 node and 28 links network, based on a French National Research Network, deployed for the project VTHD (*Vraiment Très Haut Débit*) [11].

We generate traffic demands for all pairs of nodes in the networks by using independent uniform random variables distributed in the interval [0, *maxload*]. We chose values for *maxload* such that the results show the network under light load, where all links are relatively unloaded; and under high load, where many links are loaded at their nominal capacity.

It is interesting to note that the solutions are not unique; more than one LSP layout may yield the same bus-LSP count and optimal bandwidth use. Even when dealing with homogeneous symmetric traffic matrixes, the layout provided by the optimal solution is not always symmetric: there is not necessarily a reverse matching bus-LSP for every bus-LSP.

Table 1 provides numerical results for the MCL case. The main result here is the reduction of the number of required LSPs which, under high traffic loads, is brought down from 12 to 3 for NET1 and from 110 to 7 for NET2. Such a significant reduction in the complexity of the layout is quite important considering that the related operational costs will also decrease in an important amount.

We observe in Table 1 that the total number of flows transported by the bus-LSPs is larger than the number of commodities. The reason is that, as indicated before, load sharing is allowed between bus-LSPs.

Note that the bus-LSPs go through an important number of nodes: for NET1, they all visit all nodes, and for NET2, they visit between 6 and 10 of the 11 nodes. It is finally interesting to see that the established bus-LSPs carry a great number of demands, proving the

Table 1
MCL Results

	Network	NET1 (12 demands)		NET2 (110 demands)	
	Maxload (MBPS)	200	500	20	180
Number of bus-LSPs		2	3	5	7
Bandwidth used (Gbps)		2.02	6.21	3.75	25.83
Length of bus-LSP (in links)	Avg	3	3	7.8	7.57
	Max	3	3	9	9
Number of demands running on bus-LSP	Avg	6	4.33	22	17.29
	Max	6	5	34	23
Number of demands running on each link	Avg	2	1.9	14.32	11.93
	Max	4	4	32	16

fact that there is a good reuse factor of a bus-FAs; the average number of demands running on a link actually proves this point as well. This reuse factor however decreases as the load increases, because the links along the bus saturate and cannot convey any more demands.

We now will discuss the MCL-BC problem. For the simulations of this problem, we set the value of Δ (see Equation 10) to 1/10,000 of the value of the optimal bandwidth utilization. We used here the same traffic matrixes as those generated for the study of MCL so as to compare results between both methods.

First of all, the number of bus-LSPs required here is notably larger than in the previous case. However, the gain is still important, reducing the number of LSPs from 12 to 4 for NET1 and from 110 to 14 for NET2.

The second very important result is the bandwidth utilization. When solving the MCL-BC, the bandwidth utilization is at least 23% less than when solving the MCL. This therefore may justify the use of the MCL-BC as a traffic engineering tool, as it simultaneously gives a good utilization of the network resources and reduces the operational costs by simplifying the layout.

It is interesting to remark that in our examples the number of required bus-LSPs does not vary with the load. This is of course not always the case, but happens quasi-systematically when the demand matrixes are generated uniformly. As with the MCL problem, the average length of bus-LSPs is reduced when the load increases, as some very important demands will fill a link to nominal capacity, preventing any other demand from using it: this generates shorter bus-FAs. On average, the number of demands running on each bus-LSP and on each link has reduced, which comes from the fact that the load is spread out more evenly so as to

Table 2
MCL-BC Results

	Network	NET1 (12 demands)		NET2 (110 demands)	
	Maxload (MBps)	200	500	20	180
Number of bus-LSPs		4	4	14	14
Bandwidth used (Gbps)		1.48	4.72	2.14	19.80
Length of bus-LSP (in links)	Avg	3	2.75	6.6	6.5
	Max	3	3	8	9
Number of demands running on bus-LSP	Avg	3	2	7.86	8
	Max	3	3	11	14
Number of demands running on each link	Avg	1.4	1.4	8.21	8.43
	Max	2	2	11	12

allow better bandwidth utilization.

6. CONCLUSION

In this paper we analyzed the benefits of introducing bus-LSPs in a GMPLS network. We show that this concept allows for reducing both the OPEX and CAPEX and we evaluated quantitatively this gain for two network topologies in the non-routed case. For this purpose, we have formulated and analyzed two mixed-integer linear programs which are realistic models of the analyzed networks.

We are currently working on an optimal design for the routed case. As these bus-LSPs are to be integrated in GMPLS controlled routed multilayer networks, we are currently studying both the layout complexity reduction and the resource savings bus-LSPs can provide in such networks. We are also working on the case of time-varying traffic models to better match the fact that in next generation networks the ratio between access links and core links capacity increases and traffic in the core won't be as shaped as it is today.

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