Deployment and Validation of GMPLS-Controlled Multi-layer Integrated Routing over the ASON/GMPLS CARISMA Test-bed

Fernando Agraz, Luis Velasco, Jordi Perelló, Marc Ruiz, Salvatore Spadaro, Gabriel Junyent and Jaume Comellas
Advanced Broadband Communications Center (CCABA), Universitat Politècnica de Catalunya (UPC), Barcelona, Spain
Email: comellas@tsc.upc.edu

Abstract— The efficient accommodation of sub-wavelength client flows on optical channels is a current challenge for the optimization of resources in GMPLS-controlled optical networks. While the capacity of the optical channels usually exceeds 10 Gbps, connection requests show finer granularity. This paper concentrates on the design and implementation of the ASON/GMPLS CARISMA test-bed a GMPLS-controlled grooming-capable transport network. Through the paper, the operation of a GMPLS-controlled multi-layer network architecture is introduced, reviewing those implementation issues that come into light. Then, an experimental evaluation is conducted on two alternative network scenarios with different number of nodes and nodal degree. From the results, GMPLS-controlled grooming makes a good trade-off between network blocking probability and E/O port usage when compared to all-optical and opaque solutions, leading to enhanced network performance while reducing network capital expenditures (CAPEX).

Index Terms— GMPLS, multi-layer networks, sub-wavelength client flows, network test-bed.

I. INTRODUCTION

Wavelength-routed optical networks have received increasing attention as a promising approach to deploy end-to-end transparent networks in a cost-effective way. The definition of the ITU-T Automatically Switched Optical Network (ASON) architecture [1], allows wavelength-routed optical networks to include dynamic connection capability. This capability is accomplished by means of a control plane entity, responsible for the establishment, maintenance and release of connections over the optical transport plane.

In parallel, the Internet Engineering Task Force (IETF) has standardized Generalized Multi-Protocol Label Switching (GMPLS, [2]) as a set of protocols to implement a common control plane, able to manage several switching technologies in an integrated way. GMPLS is the most widely accepted solution to implement the control plane functionalities in the ASON architecture. These ASON networks with a GMPLS-enabled control plane are typically referred as ASON/GMPLS networks.

The role of IP as a convergent technology has triggered the development of a wide range of new multimedia services, like HDTV, video conference, teledmedicine applications or Internet telephony, having each one different Quality of Service (QoS) requirements. This huge, heterogeneous and predominantly bursty generated traffic poses new challenges to network operators to provide a cost-effective data transmission. Because the bandwidth granularity of wavelength-routed optical networks is very coarse, typically a whole wavelength supporting 10 or even 40 Gbps, these networks lack the flexibility to support sub-wavelength traffic demands, which leads to a poor bandwidth usage.

In this context, the term traffic grooming identifies the process of packing several low-speed traffic streams into higher-speed streams, trying to maximize optical channels bandwidth usage in Dense Wavelength Division Multiplexing (DWDM) meshed transport networks [3], [4]. From the GMPLS point of view, the grooming problem is translated into merging several higher-order Label Switched Paths (LSPs) into a lower-order LSP (e.g., grooming packet LSPs carrying IP traffic into a λ-LSP). Such an LSP aggregation in GMPLS is accomplished by advertising newly created lower-order LSPs as Forwarding Adjacency LSPs (FA-LSPs, [5],[6]), for instance, by means of the OSPF-TE protocol [7]. In this way, conventional data-links (coming from wavelength channels) along with the previously advertised FA-LSPs can indistinctly enter the path computation process. Supposing that a valid route would be found, resource reservation would then be performed by RSVP-TE [8].

The goal of this paper is to introduce the design and implementation of the grooming-capable ASON/GMPLS CARISMA test-bed. To this end, section 2 introduces the
FA-LSP concept defining a routing metric and a cost function. Section 3 details the scenario where this integrated multi-layer routing has been evaluated also reviewing the implementation of the FA-LSP functionalities. Then, section 4 presents the obtained experimental results. Finally, section 5 concludes the paper.

II. MULTILAYER ROUTING THROUGH FA-LSPs

From an architectural point of view, the control plane in multi-layer networks can follow three differentiated models namely overlay, augmented and peer [6]. In the traditional overlay model different control plane instances run on each layer. Thus, they are independently controlled. Alternatively, in the augmented approach, different control plane instances run on each layer but some information is exchanged amongst them, aiming at improved bandwidth allocation in the network. Finally, in the peer approach all layers are controlled by a unified control plane, and decisions are taken considering whole network information.

The enhanced TE protocols introduced in GMPLS pave the way to peer multi-layer network architectures, controlled by means of a GMPLS-enabled common control plane. The enabling entity to this goal is the FA. In GMPLS, those already established lower layer LSPs (e.g., \( \lambda \)-LSPs) are advertised as FA-LSPs, which can be used to transport new sub-wavelength client LSPs. In this way, lower layer resources can be effectively utilized.

Fig. 1 shows an example of a two-layered network peer architecture, particularly, an optical server layer and a client aggregation layer on top (e.g., SONET/SDH, MPLS, GbE etc.). At the bottom, optical nodes provide DWDM ports as well as client access ports, used to inject an aggregated client flow to the network. In this context, an incoming signal would be adapted, switched to a DWDM port, multiplexed into a DWDM bundle and finally transmitted to the downstream optical node. On top, the client aggregation layer includes generic nodes providing electrical switching, flow aggregation and other features. Client nodes are connected to optical nodes through the client access ports.

In current GMPLS standardization [2] there is an intrinsic association between the signaling of new client LSPs and the creation of the required \( \lambda \)-LSP to support them. As will be later detailed, a route from source to destination is computed upon client LSP request, which may be constituted of both unallocated data links and already existent FA-LSPs. In the case that no FA-LSP is comprised along the route, a new \( \lambda \)-LSP is typically set-up from source to destination to support the incoming request. Otherwise, \( \lambda \)-LSPs are set-up to provide connectivity on those route segments where no FA-LSP is yet established. This operation, however, may lead to resource waste in the network. Notice that long FA-LSPs connecting far-off nodes are limited to be only reused by incoming LSP requests between remote endpoints. Hence, it appears more appropriate to separate the signaling functionality from the \( \lambda \)-LSP creation, so that \( \lambda \)-LSP placement can be decided based on network characteristics.

In the present paper, we set the routing metric of the already established FA-LSPs to be \( \max\{1, \text{hops}(\lambda\text{-LSP})\} \), as described in [5]. Besides, the routing metric assigned to the unallocated data links spanning one single physical hop is set to 1. Aiming at better resource utilization, however, we dissociate \( \lambda \)-LSP establishment from network signaling functionality in the following way. Once the route from source to destination is calculated, the heuristic cost function \( C_{\text{FA}}(H) = H [(1-p_H) + h/H] \) is applied to the route segments where connectivity is not yet existent, standing \( H \) for the number of hops of the yet to be created \( \lambda \)-LSP and \( p_H \) for the probability that any incoming demand in the network has a certain number of hops \( H \).

The cost function provides us with the most appropriate \( \lambda \)-LSP configuration to optically connect the yet uncovered route segment. As will be later depicted by example, the term \((1-p_H)\) encourages those \( \lambda \)-LSP lengths close to the average network distance, thus being more likely to be reused. The term \( H/h \) identifies the use of O/E port pairs per hop, so that the larger the \( \lambda \)-LSP, the lower the use of O/E ports to connect its endpoints. The tunable \( h \) parameter fosters/penalizes the use of O/E ports in the network. Finally, the total cost is multiplied by \( H \) as longer \( \lambda \)-LSPs need a higher number of unallocated data links. In this context, let us imagine that a new \( \lambda \)-LSP, which will afterwards act as FA-LSP, has to be established between a node-pair distancing 4 hops. Supposing that a 2 hops client LSP length is the most likely in the network, the combination \( C_{\text{FA}}(2) + C_{\text{FA}}(2) \), that is, two \( \lambda \)-LSPs spanning each one two hops, could have lower cost than \( C_{\text{FA}}(4) \), meaning one single end-to-end \( \lambda \)-LSP. Very short FA-LSP establishment (e.g., 1 hop) is also penalized in \( C_{\text{FA}}(H) \), due to the large amount of expensive O/E ports required, as well as the huge amount of bypass traffic to be electrically processed.

III. IMPLEMENTATION OF THE GMPLS-CONTROLLED MULTI-LAYER INTEGRATED ROUTING

The experimental evaluation of the GMPLS integrated routing functionality has been carried out over the ASON/GMPLS CARISMA test-bed [11], a configurable
multi-topology Signaling Communications Network (SCN) running over Optical Cross-Connect (OXC) emulators. In this configurable SCN, Optical Connection Controllers (OCCs) are interconnected by 100 Mbps full-duplex Ethernet links, describing the same topology than the underlying transport plane. In the test-bed, OCCs are deployed by means of Pentium IV Linux-based routers at 2-GHz, so that each OCC implements the full GMPLS protocol set: RSVP-TE for signaling, OSPF-TE for routing and information advertisement LMP for resource discovery and management [12].

Fig. 2 depicts the OCC architecture in the CARISMA test-bed, highlighting the standards followed on each composing module to achieve the desired operation. Each OCC contains three modules that interact among them: the Link Resource Manager (LRM), the Routing Controller (RC) and the Connection Controller (CC).

The LRM module is responsible for the management of the resources available at the optical node. Specifically, the state of the transport plane resources is stored in the Management Information Base (MIB). The OXC Manager module synchronizes the state of these resources with the optical node through the Connection Controller Interface (CCI). The same interface is used by the node to notify alarms using Simple Network Management Protocol (SNMP) traps [13]. Moreover, the LRM contains the LMP module that implements the GMPLS LMP protocol, and the LRM server module, which implements communication interfaces to the RC and CC modules in the same OCC.

The RC, basically, is the responsible for computing transport plane routes. It implements several routing algorithms to compute transport plane routes. In this regard, it is worth noting that the CARISMA network test-bed uses differentiate addressing spaces at the control plane and at the transport plane. In fact, the quagga OSPF module [14] implements the OSPFv2 protocol which floods links state information related to the control plane IP network. In contrast, the RC floods the state of the local output data-links to the rest of control plane OCCs using OSPF-TE Opaque Link State Advertisements (OLSAs, [7], [15]). The information in the OLSAs is related to the transport plane and stored in the TE database (TEDB). OLSA flooding is performed every time a data-link is allocated or released. The RC module implements communication interfaces to the CC and LRM. The CC requires route computation between two end nodes, whereas the LRM notifies the RC about the reservation, release or failure of the local resources, which imply OLSA flooding.

Finally, the CC is responsible for the LSP set-up and tear-down. The CC module includes the RSVP module which implements the RSVP-TE protocol [8], [10]. The CC contains the Path State Block (PSB) database which stores every LSP supported on local resources. The Network Management System (NMS) communicates with the CC through the NMI-A interface to request set-up or tear-down connections. Upon receiving a connection set-up command towards a remote node, the CC asks the RC for a transport plane valid route to that node. Then, every CC on the route to the destination must ask the LRM about the availability of the local resources and eventually request them to be allocated.

The implementation of the FA-LSP functionality at the control plane of the CARISMA test-bed has been made...
according to GMPLS standards. A new RSVP-TE object LSP_TUNNEL_INTERFACE_ID was proposed to be used when signaling a new FA-LSP in the Path and Resv RSVP-TE messages [10]. The object contains two fields, that is, the FA-LSP identifier and the router ID.

In the event of a new λ-LSP to be set up, the head-end OCC must allocate an identifier for the interface associated to the yet to be created FA-LSP. Next, it originates an RSVP-TE Path message containing a LSP_TUNNEL_INTERFACE_ID object filled with the selected local interface identifier, along with the local optical node identifier. When the Path message arrives to the destination, the tail-end OCC must allocate an identifier for that FA-LSP end. This is called the remote FA-LSP interface identifier, which is reported back to the head-end within the RSVP-TE Resv message. As soon as the λ-LSP has been created, the head-end OCC advertises it as a forwarding adjacency by means of OSPF-TE. Being the FA-LSP bidirectional, it is also advertised by the tail-end OCC. All OCCs receiving the FA advertisement update its link state database adding a new link between the involved nodes. As an example, Fig. 3 depicts the signaling procedures between nodes A-F involving an existing FA-LSP between B-E. In this case, two new λ-LSPs (A-B, E-F) must be established to support the client LSP A-F, which will re-use part of the spare capacity in the FA-LSP B-E.

As mentioned before, λ-LSP’s length may be limited to maximize resource re-utilization in the network. To achieve such purposes, λ-LSP establishment must be dissociated from the client LSP setup procedure, allowing in this way the establishment of several underlying λ-LSPs while signaling only one client LSP request. To permit this separation between client and λ-LSP set-up, the head-end OCC evaluates the accumulated optical length, using loose hops in the ERO RSVP-TE object [8], deciding whether or not the whole route segment has to be divided into several underlying λ-LSPs. The same mechanism is also adopted when an intermediate λ-LSP should be created. Receiving an intermediate OCC an RSVP-TE Path message with the next hop set as loose, it must perform a route expansion computing the next route segment and decide if it should be divided into several underlying λ-LSPs.

In this work, both the CC and the RC CARISMA modules have been enhanced with the RSVP-TE extensions and the routing metric detailed above. After a new λ-LSP is established, OSPF-TE flooding updates the new state of those allocated wavelength-channels, also advertising the residual available bandwidth on the newly created FA-LSP. This FA-LSP will be available for route computation until the residual available bandwidth becomes zero or it does not support any client LSP, when the subjacent λ-LSP will automatically be torn down.

IV. EXPERIMENTAL RESULTS

For the evaluation, two different transport network topologies have been considered: a medium-sized topology composed of 9 nodes and 11 links (Fig. 4, left), and a larger one with 16 nodes and 23 links (Fig. 4, right). In both scenarios, each link supports 8 bidirectional wavelengths.

Departing from these basic network scenarios, three different architectural solutions have been analyzed: all-optical, generic FA and opaque. The first solution stands for an all-optical network, where an end-to-end light-path with the whole wavelength capacity is established per client LSP request. The second solution, generic FA, identifies the GMPLS-controlled traffic grooming exactly as explained in the previous section. Finally, the third solution contemplates an opaque transport network, where only single-hop λ-LSPs are allowed. Once established, these LSPs are advertised as FA-LSPs permitting their re-use.

For the traffic characteristics, we consider that uniformly distributed client LSP requests arrive to the network following a Poisson process with mean Inter-Arrival Time (IAT) equal to 1/λ. Besides, connection duration follows an exponential distribution with mean Holding Time (HT) set to 1/µ. In particular, the requested BW of all incoming client LSP requests is considered to be 1/4 of the total wavelength capacity.

Fig. 5 illustrates the obtained C(H) function for the 9-Node network topology. The bar graph plots the probability that an incoming client LSP request has a certain number of hops, assuming availability of resources through the shortest path. As seen, there is a 40% probability that an incoming request traverses 2 hops from source to destination. In contrast, only 5% of the incoming requests would traverse 4 hops. This validates our assumptions where we stated that, by splitting very long FA-LSPs into shorter one’s resources are much more likely to be reused. Values greater than the network diameter (i.e., 4 hops in our scenario) have p_H = 0.0 and are not depicted in the figure. To finally obtain CEAF(H) we fix h = 0.5, as it provided the best network performance, while fulfilling our design criteria: CEAF(2) + CEAF(2) < CEAF(4) and CEAF(1) + CEAF(2) < CEAF(3).

For each architectural solution, Fig. 6 plots the obtained client LSP blocking probability in the 9-Node network topology as a function of the offered load to the
Fig. 4 9-Node (left) and 16-Node (right) transport networks under evaluation.

Fig. 5 $C_{FA}(H)$ function in the 9-Node network topology.

Fig. 6 Blocking probability vs. offered load in the 9-Node network topology.

Fig. 7 Blocking probability vs. offered load in the 16-Node network topology.

Fig. 8 O/E port usage vs. offered load in the 16-Node network topology.
network ($\lambda/\mu = HT/IAT$), normalized to a value of 200. As expected, significantly better resource usage is achieved when implementing FA-LSP capabilities in the network. For instance, if 0.5% client LSP blocking probability would have to be assured, a maximum load $L = 0.02$ could be offered to a pure all-optical wavelength-routed optical network. Conversely, it could be further increased to $L = 0.5$ when FA-LSPs are implemented, almost overlapping the opaque solution. This $\Delta L = 0.48$ assesses experimentally the FA-LSP capabilities to automatically manage grooming actions in future transport networks, given the limitations of pure wavelength-routed optical networks to allocate incoming sub-lambda client LSP requests. In fact, as a whole wavelength is allocated in per 1/4 wavelength capacity client LSP request in the all-optical architecture, 3/4 of the total network capacity is directly wasted. Qualitatively speaking, this approximately results in four times less carried traffic by the network.

Fig. 7 shows the blocking probability results for each architectural solution, now in the 16-Node network topology. Moreover, $C_{F,D}(H)$ has been particularized to let generic FA obtain the best performance. Again, the blocking probability figures are drastically reduced when implementing the FA-LSP functionality in the network. Here, fixing a blocking probability value around 0.5%, the offered load to the network in the generic FA and opaque solutions can be increased by 0.6 compared to the all-optical one.

As seen, generic FA and opaque solutions provide similar blocking probabilities in both 9-Node and 16-Node network scenarios. In order to also envisage the related network CAPEX in all-optical, generic FA and opaque solutions, Fig. 8 quantifies the E/O port usage in the 16-Node network topology. To this end, the Y axis has been normalized to the maximum number of E/O ports that could be equipped in the network (one per output wavelength at each node).

As seen, besides pleading for huge electronic routers, able to process all the incoming information at the nodes, the opaque solution rapidly requires a large number of E/O ports, since an optical bypass is not possible in the network. Conversely, although the all-optical solution leads to the lowest port usage, this is mandated by its poor bandwidth efficiency, which forces it to consume all available wavelength channels. Interestingly, the generic FA lies between both solutions. As seen before, it leads to similar PB than the opaque solution. Nonetheless, thanks to the optical bypass capability, it leads to a lower E/O port usage, thus reducing the total CAPEX. Note that for an offered load of 0.7, leading to the same PB around 0.5%, the E/O port usage is decreased by 15%.

V. CONCLUSIONS AND FUTURE WORK

This paper reported the implementation and experimental validation of the CARISMA test-bed, a GMPLS-controlled grooming-capable network. To start with, the paper reviewed the Forwarding Adjacency (FA) entity, further elaborating on a FA creation cost function $C_{F,D}(H)$ that dissociates the $\lambda$-LSP set up from the network signaling process, enhancing in this way the reuse of already established FA-LSPs.

For evaluation purposes, two alternative network scenarios have been configured, namely, a medium-sized 9-Node network and a larger one composed of 16 nodes. In particular, the 9-Node network has served to exemplify the rationale behind the dissociation between client and $\lambda$-LSP establishments according to the $C_{F,D}(H)$ function. From the obtained experimental results, GMPLS-controlled multi-layer integrated routing drastically improves the network blocking probability compared to an all-optical network solution. Moreover, these benefits increase as the network topology gets larger, as identified when moving from the 9-Node to the 16-Node network. Compared to an opaque network solution the resulting network blocking probability remains almost equal. However, we have obtained that thanks to the optical bypass capability, GMPLS-controlled multi-layer integrated routing leads to lower E/O port usage, which is translated into lower network CAPEX.

The evaluation presented in this paper concerns single 9-Node and 16-Node ASON domains. Further work will extend the implementation of the FA-LSP functionality in larger multi-domain multi-layer network environments. It will be our goal to assess not only the performance, but also the scalability of the GMPLS-controlled grooming as the network gets larger, even spanning more than a single domain.

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