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R. Muñoz, C. Pinart, R. Martínez, J. Sorribes, M. Maier, A. Amrani, G. Junyent

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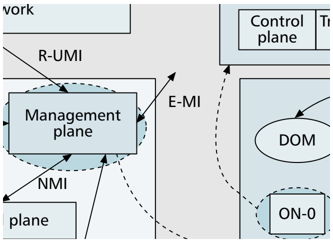

THE ADRENALINE TESTBED: INTEGRATING GMPLS, XML, AND SNMP IN TRANSPARENT DWDM NETWORKS

Raül Munoz, Carolina Pinart, and Ricardo Martínez, Centre Tecnòlogic de Telecomunicacions de Catalunya
Jordi Sorribes and Gabriel Junyent, Universitat Politècnica de Catalunya
Martin Maier, INRS-EMT
Abdelhafid Amrani, Médi Télécom

ABSTRACT

This article presents a brief overview, state of the art, and taxonomy of optical WDM testbeds, and outlines the differences between them and the ADRENALINE testbed. ADRENALINE is an optical circuit-switched WDM testbed that deploys reconfigurable OADMs based on various technologies (e.g., AWG and tunable lasers). In ADRENALINE, end-to-end lightpaths are set up and torn down dynamically and in real time by means of a GMPLS-based control plane (switched connections) and a distributed management plane (soft-permanent connections). ADRENALINE supports the request of SPCs under user initiative by combining GMPLS, SNMP, and XML. ADRENALINE allows both the topology and major characteristics of the data communications network to be modified, enabling control and management related experiments with varying DCN. In our experiments we investigate user management of lightpaths and address its performance in terms of basic SLA parameters related to connection establishment (delay and availability). Finally, we address remaining challenges and outline exciting avenues of future work on ADRENALINE.

INTRODUCTION

The accelerating growth of data traffic is motivating research and development of more efficient, flexible, intelligent optical networks and protocols. To meet these challenges, IP over wavelength-division multiplexing (IP/WDM) networks are widely accepted to be a very promising solution. There is a wide range of clients of IP/WDM networks (IP routers, asynchronous transfer mode [ATM] switches, etc.) that are interconnected by means of optical wavelength channels, so-called lightpaths. To control such lightpaths in a dynamic, efficient, and real-time manner, generalized multiprotocol label switching (GMPLS) has attracted considerable attention. A GMPLS-based control plane in conjunction with optical management functions allows the dynamic traffic demands of various clients to be satisfied by means of so-called soft permanent connections (SPCs) and switched connections (SCs). In both cases connections are established by means of the signaling and routing protocols of the GMPLS-based control plane, but in the former the connections are triggered by the network management system (NMS), and in the latter connections are triggered automatically by the client equipment itself by means of the user–network interface (UNI).

In this article we describe the GMPLS-based control plane as well as the management and transport planes of our proposed optical WDM testbed, named ADRENALINE. In particular, we focus on the interaction of the management plane with both remote SPC provisioning requests and the control plane through integrating Extensible Markup Language (XML) and Simple Network Management Protocol (SNMP) based communication mechanisms in the management plane and coordinating these mechanisms with GMPLS used in the control plane.

The remainder of the article is organized as follows. We provide an overview and taxonomy of existing WDM testbed activities and highlight the salient differences between them and ADRENALINE, which is described in greater detail. We provide experimental results on the user management of lightpaths in ADRENALINE. Remaining challenges and future work are addressed. We then conclude the article.

RELATED TESTBED ACTIVITIES

Previously reported optical WDM testbeds can be categorized into packet-switched, flow-switched, and circuit-switched networks. Among others, HORNET is an example of variable-

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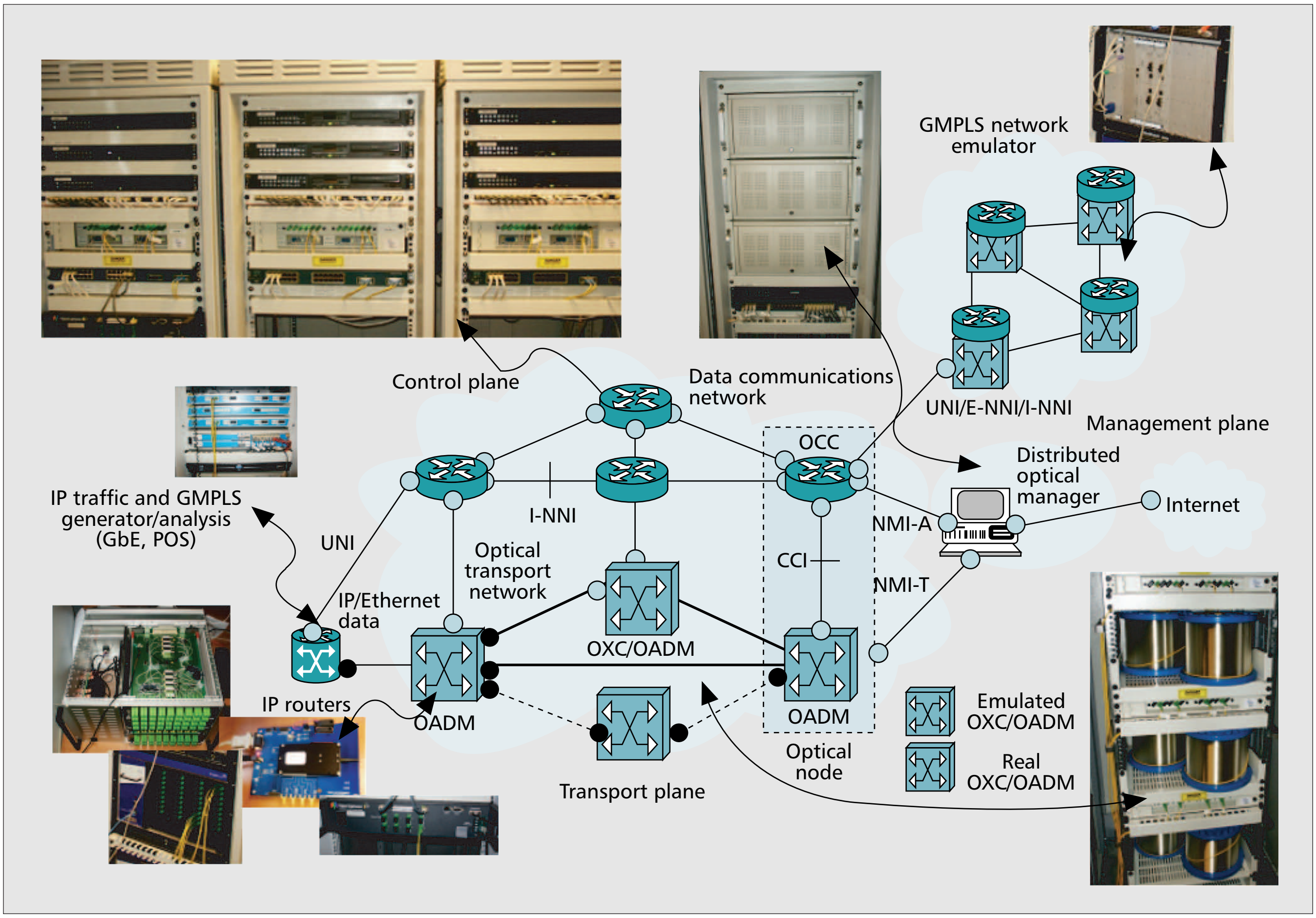

FIGURE 1. Logical architecture and main elements of the ADRENALINE testbed.

size packet-over-WDM bidirectional ring networks [1]. Besides survivability, fairness, and feasibility issues HORNET also addresses dynamic wavelength channel access by means of distributed media access control (MAC) protocols. In HORNET, nodes deploy either carrier sense multiple access with collision avoidance (CSMA/CA) or a control-channel-based MAC protocol to arbitrate wavelength channel access. RingO is another example of an experimental optical WDM packet-switched ring network that arbitrates wavelength channel access by means of a distributed MAC protocol [2]. In RingO, all wavelength channels are divided into equally sized time slots, whose size equals the transmission time of a fixed-size packet. Nodes deploy an *empty-slot* MAC protocol, where every node checks the state (busy/free) of each slot on all wavelength channels prior to transmitting data packets. A given node is allowed to send locally generated data packets only in free slots, thereby preventing channel collisions. The NGI ONRAMP testbed introduces the concept of *optical flow switching*. In optical flow switching, a large set of data is routed all-optically in order to bypass intermediate routers. Upon detection of a large-volume flow, a dedicated end-to-end optical channel is set up, eliminating the need for (electronic) packet buffering and processing along the path. An example of circuit-switched WDM testbeds is the KomNet ring network that provides switching granularity at the wavelength channel level. By using tunable fiber Bragg grating based optical add-drop multiplexers (OADMs) the ring can be *dynamically* configured. More recently, the control and management of optical configurable networks have attracted considerable attention. The testbed of the European IST project LION provides an experimental feasibility demonstration of setup/teardown of SPCs with GMPLS signaling and resilience experiments in a managed, multivendor, multidomain environment [3]. Alternatively, in so-called *customer-owned and -managed* optical networks users are able to control and manage their own wide area optical network [4]. In such a network, users will be able to perform their own restoration and protection, optical add-drop multiplexing, or crossconnection to other users on a peer-to-peer basis without signaling or requesting service from a centrally managed entity.

The ADRENALINE testbed differs from the aforementioned testbeds in a number of ways. As described in greater detail in the next section, ADRENALINE is a circuit-switched optical WDM testbed that deploys reconfigurable OADMs based on various technologies (e.g., arrayed-waveguide gratings [AWGs] and tunable lasers). In ADRENALINE, end-to-end lightpaths are set up and torn down dynamically and in real time by means of a GMPLS-based control plane and a *distributed* management plane. ADRENALINE provides not only SPCs, as done in LION, but also SCs. Furthermore, ADRENALINE supports the request of SPCs under user initiative by combining user management of lightpaths and control plane technologies. Finally, ADRENALINE allows both the network topology and major characteristics of the data communications network (DCN) to be modified.

THE ADRENALINE TESTBED

The ADRENALINE testbed is a hybrid platform whose transport plane consists of real and *emulated* optical nodes and links, enabling experiments with a wide range of different network topologies (Fig. 1). Apart from a distributed GMPLS-based control plane, ADRENALINE deploys a distributed management plane by combining the industry standard SNMP

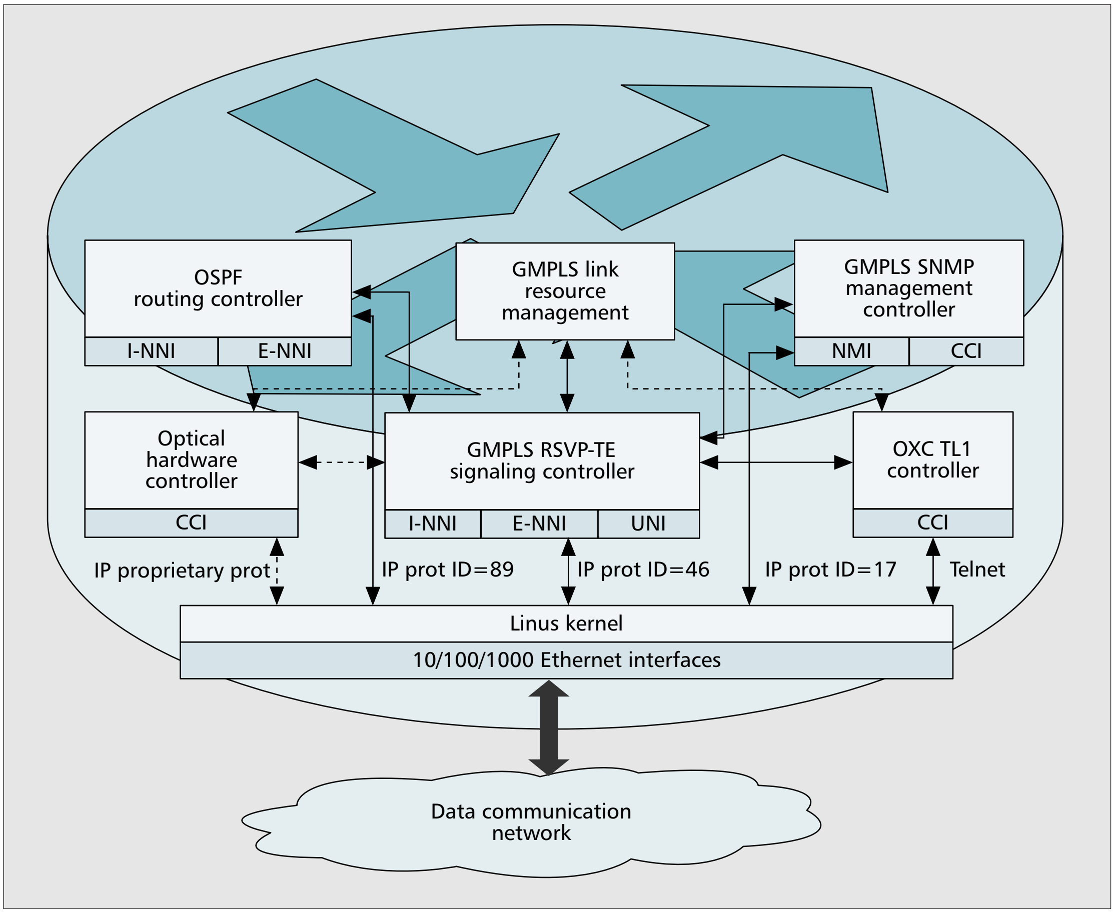

FIGURE 2. Architecture of a GMPLS-based optical connection controller (OCC).

and user-friendly (XML-based) tools, allowing users (e.g., Internet service providers, university and hospital network managers) to provision lightpaths dynamically.

THE TRANSPORT PLANE

The transport plane of ADRENALINE consists of both real and emulated optical nodes and links. Specifically, there are three real reconfigurable OADMS (R-OADMs), each capable of adding/dropping up to eight wavelengths, and two real optical crossconnects (OXCs). In the current R-OADMs, entirely designed and developed at the Centre Tecnològic de Telecomunicacions de Catalunya's (CTTC's) laboratories, the add/drop process is performed by a two-stage unit. The add/drop (first) stage filters the drop channels out of the dense WDM (DWDM) signal and adds new channels up into the ring. The distribution (second) stage assigns the added and dropped signals to the tributary interface cards of the client equipment. In the ADRENALINE testbed the add/drop stages are based on an array of eight 2 × 2 optical switches in combination with a single 18 × 18 AWG or two 1 × 16 AWGs used as an optical multiplexer and demultiplexer. The distribution stage is realized using $N \times M$ optical switching matrices, where N is the number of add/drop channels and M is the number of client tributary interfaces. Currently new advances in optical networking technology allow the add/drop and distribution stages to be merged into a single stage using integrated wavelength selective switching (WSS) technology. OXCs are composed of an 18 × 18 optical switch and an 18 × 18 AWG, and allows an optical channel to be switched from an input fiber/client tributary to any output fiber/client tributary. There are no wavelength converters, so a lightpath must occupy the same wavelength on all the fiber links it traverses (i.e., over all the path). This problem is known as the wavelength continuity constraint.

The ADRENALINE testbed counts with two 32 × 32 TL1-based optical switches. These switches, based on micro-electro-mechanical switching (MEMS) technology, can be virtually divided in order to have smaller independent optical switches that are used as the R-OADMs' distribution stages and the OXCs' optical switches, or even as additional R-OADMs or OXCs. In this way the ADRENALINE testbed has total flexibility at the transport layer, adapting the number of optical nodes to the specific tests done at each moment. All laser sources are fully tunable, except two fixed lasers used for testing purposes. Modulating the optical channels is achieved by using 2.5 Gb/s (six lasers) direct modulation. ADRENALINE deploys three optical bidirectional pairs of fiber. Each fiber is 35 km long and carries an in-fiber out-of-band control channel at 1310 nm apart from the C-band data wavelength channels. Control and management messages are sent on the control channel at a line rate of 100 Mb/s using Fast Ethernet. The emulated links carry only the control channel and are implemented out-of-fiber using network emulator software installed on a central Linux-based PC. Among other things, this software allows emulating fixed packet propagation delays, packet loss, packet duplication, and bandwidth limitations between each pair of network nodes. The emulated links can be configured dynamically based on virtual local area network (VLAN) and generic router encapsulation (GRE) tunnels, allowing different types of DCN topologies.

Finally, two broadband testers are employed for test and experimentation. The first has been programmed (based on tcl/tk scripts) and configured to emulate UNI-enabled client equipment for requesting optical connections to the testbed, and generating and analyzing IP traffic over Gigabit Ethernet (GigE) and packet over synchronous optical network (SONET: PoS). The second tester allows exterior and interior GMPLS-based networks to be emulated in order to test and stress the network at the level of the control plane. This equipment also performs conformance tests of GMPLS-based protocols.

CONTROL PLANE

An optical control plane introduces intelligence in wavelength-routed optical networks in order to provide automated provisioning and protection/restoration as well as automated optical topology and resource dissemination used for traffic engineering (TE) to allow the most efficient use of network resources. To realize a GMPLS-based distributed control plane each node has its own optical connection controller (OCC). At present, ADRENALINE deploys nine OCCs and supports the lambda switching capability (LSC). Each OCC is implemented by means of a Linux-based PC that acts as an IPv4 router with a Pentium IV 2.6 GHz processor and three GigE cards. Figure 2 shows the architecture of a GMPLS-based OCC whose interfaces — reference points according to the International Telecommunication Union — Telecommunication Standardization Sector (ITU-T) automatically switched optical network (ASON) architecture — are explained in the following. More information about the architecture can be found in [5].

Network Management Interface — This interface enables transfer of information between the control and management planes; the management plane will use such information to perform fault, configuration, accounting, performance and security (FCAPS) functions. Several approaches exist for implementing the network management interface (NMI), such as based on the SNMP protocol (Internet Engineering Task Force, IETF) or according to the Multi-Technology Management Network (TeleManagement Forum). In this work, the NMI is based on SNMP (manager-agent paradigm), and used for communication between management agents and managers, as well as among agents themselves. To this end, each GMPLS node contains a management controller that communicates with the distributed managers through the NMI for SPC requests, control plane configuration, and performance management.

User–Network Interface — The UNI is the interface between the client equipment and the optical network. It allows client equipment to request dynamic provisioning of optical connections under a client-server relationship. Currently, two standardization bodies are defining the UNI; the Optical Interworking Forum (OIF) and the IETF. OIF has defined UNI 1.0 and more recently UNI 2.0 [6] for overlay networks (so-called public UNI). The IETF has defined a GMPLS-compliant UNI for overlay-based multilayer networks (so-called private UNI) [7]. The ADRENALINE testbed has adopted the UNI proposed by the IETF. The main features of the implemented UNI are as follows:

- The signaling protocol employed is GMPLS Resource Reservation Protocol — TE (RSVP-TE). It considers a single RSVP session used throughout the UNIs and the optical networks involved in the connection. The source/destination client addresses are defined as routable addresses, and the identifier of the session is end-to-end significant.
- The routing protocol employed is GMPLS Open Shortest Path First — TE (OSPF-TE). For flexibility, the routing protocol's interactions between the clients of ADRENALINE can follow either the overlay, augmented, or peer model. Under the overlay model there is no routing between the client and the network. Under the augmented model there are actually separate routing instances in the client and the optical network, but information such as reachability (IP end client address) is passed between both layers. Lastly, under the peer model a single routing instance runs over the client and the optical domain; hence, reachability as well as TE information is exchanged between them.

Network–Node Interface — The NNI interface is split into the internal NNI (I-NNI) and external NNI (E-NNI). The I-NNI is related to the interface between nodes that belong to the same administrative domain (e.g., vendor), and the E-NNI is related to the interface between nodes that do not belong to the same administrative domain, but whose domains belong to the same autonomous system (e.g., carrier). Normally the I-NNI is based on vendor's choice, and therefore is out of the scope of standardization bodies and could also rely on proprietary protocols. Currently the OIF has defined E-NNI 1.0 [8], and the IETF has defined a GMPLS-compliant NNI based on a peer model (I-NNI) and augmented model (E-NNI). The implemented NNI is based on GMPLS signaling and routing functions according to the IETF, but also incorporates proprietary extensions to OSPF-TE and RSVP-TE. The main features of the NNI are as follows:

- The signaling protocol employed is GMPLS RSVP-TE [9], which supports both SPCs and SCs. In GMPLS the signaling phase consists of a generalized label request, sent in a RSVP Path message, traversing hop by hop from the source node to the destination node, followed by a generalized label assignment, sent in a RSVP Resv message, traversing in the opposite direction back to the source. In addition, we have proposed some signaling enhancements such as the provisioning and protection schemes for metropolitan R-OADM DPRings [10].
- The utilized routing protocol is the GMPLS OSPF-TE through I-NNI (within a single domain) and OSPFv2 through E-NNI (across domain boundaries). Besides the existing GMPLS OSPF-TE [11], new extensions are added to the routing protocol to collect not only reachability and network topology information but also TE and resource information which are used by the corresponding routing algorithm for computing optimal intra-domain routes under possible constraints such as wavelength continuity, optical impairments, etc. On the other hand, the classical OSPFv2 through the E-NNI provides reachability and abstract topology information but neither TE nor optical resource information is shared among different domains, which is critical to preserve the routing protocol stability and confidentiality.

Connection Control Interface — The connection control interface (CCI) is the interface between the control plane and the optical hardware of the node for monitoring and configuring purposes. The spectrum of protocols that can be employed at the CCI is quite large; however, in the last years there has been a common effort for standardizing this interface based on the General Switch Management Protocol (GSMP) [12]. In the ADRENALINE testbed a proprietary protocol based on IP is employed for the implemented R-OADMs and tunable lasers. The OXCs are configured and monitored using TL1.

MANAGEMENT PLANE

ADRENALINE's management plane is modeled in three layers of distribution. The first layer is the distribution of connection requests by means of user interfaces and remote soft-permanent requests (triggered by the management plane and established using the dynamic mechanisms of the control plane). The second layer is the decentralization of the management system by using distributed managers. Instead of having an umbrella NMS, optical managers are spread throughout the network. Finally, the third layer performs efficient function allocation and decentralization of management information in order to avoid data duplication and optimize service

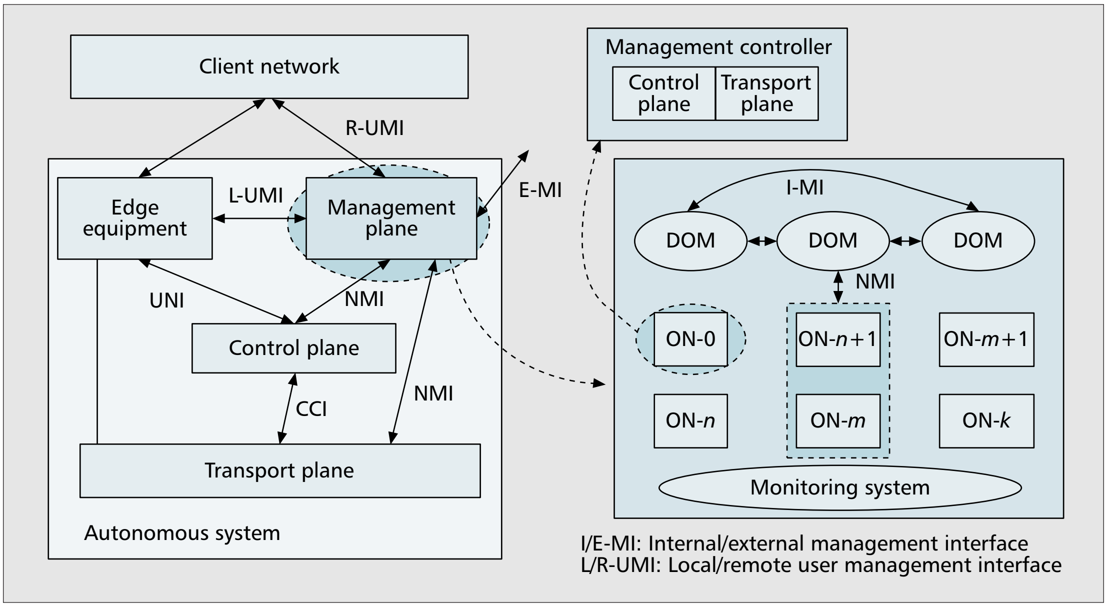

FIGURE 3. Distributed management plane.

performance. Figure 3 illustrates the architecture of the proposed distributed management plane. The three layers of distribution together with their interfaces are described in greater detail below.

User-Driven Provisioning Requests — This layer decentralizes connection requests such that users, agnostic to optical network resources and management, are able to point and click for a service. This results in the need for combining the classical management-agent paradigm (e.g., SNMP) and service-oriented technologies such as XML. Hence, this layer combines a SOAP/XML interface between users and the management plane (local and remote user–management interface, L-UMI and R-UMI in Fig. 3) and the NMI (based on SNMP). SPC requests in the ADRENALINE testbed are requested by the users through interfaces that enable transfer of information between user applications and the distributed optical managers (DOMs) of the network (L- and R-UMI). In order to send requests to the DOMs through the R-UMI, users need to have Internet access (asymmetric digital subscriber line [ADSL], fiber, etc.). If user applications are SOAP-enabled, they will send SOAP/XML requests to a SOAP server, which in turn will forward them to the DOM through the DCN. Otherwise, users can log onto a Web site and fill in a request form, which generates a SOAP/XML request that is sent to the server. The L-UMI does not require Internet access, and is meant for SOAP-enabled user equipment directly linked to the optical network (i.e., requests reach the DOM through the DCN). Once in the distributed managers, the NMI is used to transfer the requests to the control plane, and then the connections are established and torn down using GMPLS mechanisms (NNI and CCI interfaces, Fig. 3). The ADRENALINE testbed employs ADSL, cable, or fiber access technologies to connect users with distributed managers. For more information on modeling the interactions between an ASON management plane and both user-driven soft permanent requests and optical nodes, the interested reader is referred to [13].

Avoidance of Centralized Management — ADRENALINE's management system, compliant with ITU-T G.8080, is composed of DOMs that act on the control and transport planes as a gateway which is responsible for proxying with remote soft permanent connection requests, and agents (management controllers) located at each optical node. Although the internetworking of DOMs may resemble the typical network/domain management systems relationship, there is no hierarchy among them. Each DOM gathers information of a network partition (e.g., administrative area) and interacts with other DOMs through suitable interfaces (Fig. 3): interior management interface (I-MI) within an autonomous system and exterior management interface (E-MI) with external networks. Performance monitoring is performed by a distributed hybrid system composed of monitoring gatherers that collect optical analog data and digital performance information as well as data about network utilization, as well as event managers, which communicate with the DOMs through the I-MI.

Function Allocation and Decentralization of Information — ADRENALINE's optical nodes contain an agent, called the *management controller*, which communicates with the DOMs and gatherers through the NMI. The advent of the control plane and reconfigurable optical hardware moves and adds functions to the network. Moreover, the control plane has a number of mechanisms with functionality similar to traditional management functions, such as path computation and service discovery, achieved by means of signaling and routing protocols. Therefore, efficient function allocation between management agents and control plane modules is crucial. We approach control management planes' interactions as complementary (i.e., avoiding copying control plane data into managed objects) to allow the control plane to provide dynamic, fast, reliable, end-to-end IP paths over lightpaths through shared network management by the control (real-time) and management (near-real-time) planes. Such interactions are based on the following facts:

- Low-complexity modeling of data
- Management of new elements (e.g., control plane routers, optical hardware like OADMs, which are not found in current IP/WDM networks)
- Efficient allocation of management functions (soft permanent connection trigger, performance monitoring, and element configuration, excluding services)

EXPERIMENTAL RESULTS

The main research focus of ADRENALINE is the implementation and experimental investigation of the GMPLS-based control plane and distributed management plane using

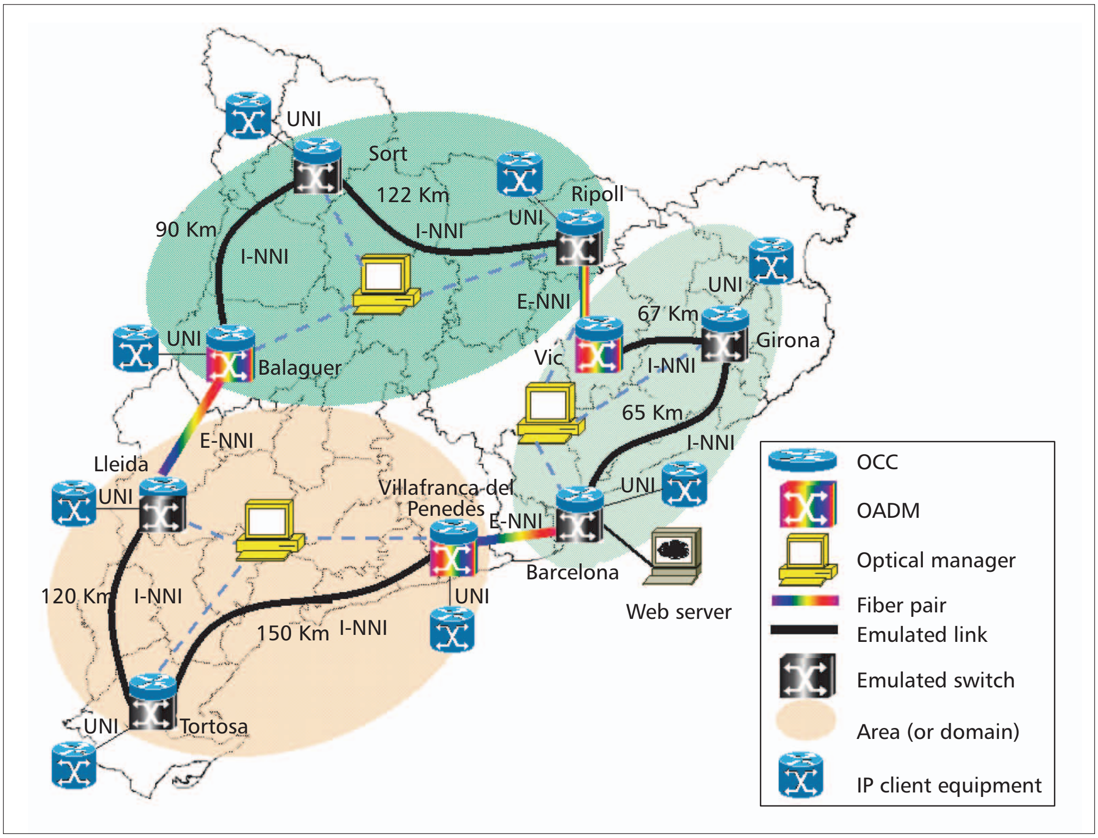

FIGURE 4. Reference network topology for the experimental performance evaluation.

SNMP and XML in order to detect unforeseen problems and examine possible solutions. In this article, we concentrate on efficiently supporting the increasing IP data traffic amount and dynamics by evaluating user management of lightpaths using GMPLS, SNMP, and XML, as explained earlier. Figure 4 illustrates the reference network topology for this performance evaluation, which is composed by a ring network implemented using 3 real links and 6 emulated links. This topology emulates the entire Catalan region of Spain through careful placing of optical nodes and links using the ADRENALINE testbed. Note that the circumference of the ring is suitable for a metro core network.

USER MANAGEMENT OF LIGHTPATHS USING GMPLS, SNMP, AND XML

Traffic demands are not only growing but also getting increasingly dynamic due to emerging applications such as e-learning, tele-medicine, and storage area networks (SANs), and the growing dominance of IP traffic. Bandwidth requirements of today's Internet service providers (ISPs) vary significantly over time. The time-of-day varying traffic pattern between office hours and home hours is an example of this variation [14]. Current optical IP/WDM networks are not able to support such highly dynamic traffic efficiently. Currently it can take up to months to provision a new connection in the network, since manual intervention is needed to change the switching pattern. As a result, the optical connection provisioning time can be minimized by the use of accommodated UMIs and distributed GMPLS-based signaling and routing protocols, such as RSVP-TE and OSPF-TE, respectively. To improve the circuit provisioning time, SPCs are requested by users through the L-UMI and R-UMI, and to satisfy dynamic traffic in an efficient manner, we propose that SCs be set up through a UNI when instantaneous traffic demands exceed the capacity of a pre-established SPC. Specifically, when traffic from a user exceeds a predefined threshold, an additional wavelength channel is established between the source-destination pair of the corresponding SPC and is torn down when the traffic level is again below the threshold. Since SCs are torn down as soon as extra capacity is no longer required, bandwidth is freed up for further requests, rendering the network adaptive to dynamic traffic in an efficient way.

PERFORMANCE EVALUATION

To examine the support of SPCs by means of temporary SCs we model dynamic traffic as follows. SPC requests arrive according to a Poisson process with mean arrival rate λ_{SPC}, and the holding time is exponentially distributed with a mean of $1/\mu_{SPC}$. Similarly, SCs are modeled with λ_{SC} and $1/\mu_{SC}$. Accordingly, the traffic loads of SPC and SC requests are equal to $\rho_{SPC} = \lambda_{SPC} \cdot 1/\mu_{SPC}$ and $\rho_{SC} = \lambda_{SC} \cdot 1/\mu_{SC}$, respectively. The total traffic load is given by $\rho = \rho_{SPC}+\rho_{SC}$. To capture the relationship of SPC and SC requests we introduce the following parameters: the mean SPC interarrival time is modeled as a fraction γ of the mean SPC holding time. In the same way, we can model the average interarrival time between two SCs belonging to the same SPC as a fraction β of the mean SC holding time. For analyzing the relationship between SPCs and SCs, we can model the mean SC holding time as a fraction α of the mean SPC holding time. We consider both uniform and hotspot traffic (parameter h). Specifically, a connection request at a given source node is destined for the hotspot node with probability $0 \leq h \leq 1$ and uniformly distributed among the remaining $(N - 2)$ nodes with equal probability $(1 - h)/(N - 2)$, where N denotes the number of nodes. In this experimentation we consider a single hotspot node that is chosen randomly from the N nodes. Table 1 summarizes the parameters of our traffic model together with their default values assigned in our subsequent experiments. The perfor-

Parameter	Description	Expression	Default value in experiments
N	Number of nodes	—	9
λ_{SPC}	SPC mean arrival rate	—	Varies with γ
$1/\mu_{SPC}$	SPC mean holding time	—	100s
λ_{SC}	SC mean arrival rate	—	Varies with β
$1/\mu_{SC}$	SC mean holding time	$\alpha \times (1/\mu_{SPC})$	10s
ρ_{SPC}	SPC traffic load	$\lambda_{SPC} \times (1/\mu_{SPC})$	Ranges from 1 to 5 Er
ρ_{SC}	SC traffic load	$\lambda_{SC} \times (1/\mu_{SC})$	Ranges from 0.1 to 2.5 Er
ρ	Total traffic load	$\rho_{SPC} + \rho_{SC}$	Ranges from 1.1 to 7.5 Er
γ	Ratio of $1/\lambda_{SPC}$ and $1/\mu_{SPC}$	$1/\lambda_{SPC} = \gamma \times 1/\mu_{SPC}$	0.2 0.4 0.6 0.8 1
α	Ratio of $1/\mu_{SPC}$ and $1/\mu_{SC}$	$1/\mu_{SC} = \alpha \times 1/\mu_{SPC}$	0.1
β	Ratio of $1/\mu_{SC}$ and $1/\lambda_{SC}$	$1/\lambda_{SC} = \beta \times 1/\mu_{SC}$	$2 \times \gamma$; $10 \times \gamma$
h	Probability that a connection request is destined for a hotspot	—	*Uniform*; 0.5

TABLE 1. Dynamic traffic model.

mance measures of interest are the mean blocking probability and mean setup delay of the end-to-end user-driven optical connection requests, which are related to SLA parameters of connection establishment delay and availability.

RESULTS AND DISCUSSION

At least in a first phase, future IP/WDM networks will be circuit-switched; therefore, it is sensible to think that future optical SLAs will contain circuit-oriented parameters, such as threshold values for the delay of establishing a lightpath. An example of this trend is [15]. On the other hand, a major parameter of current SLAs is service unavailability, which is related to the life of an optical connection (unavailability over a period of time, and recovery time). With the advent of automated provisioning tools, service unavailability will include as well the provisioning process of a service, that is, the blocking of the network (number of lightpath requests fulfilled over the total number of lightpath requests).

Figure 5 illustrates the blocking probability of the ADRENALINE testbed in uniform and hotspot traffic scenarios for user-driven (SPC) optical connections and equipment-driven (SC) connections. For evaluation purposes, we fix the mean holding time of SC as a tenth of the mean holding time of SPC ($\alpha = 0.1$). In the same way, we fix two values of β to carry out the condition that the SC load (ρ_{SC}) is 10 and 50 percent of the load of SPC (ρ_{SPC}). For an SC load of 10 percent with respect to SPC load, $\beta = 10\gamma$ since $\rho_{SPC} = 1/\gamma$ and $\rho_{SC} = 1/\beta$, and for a SC load of 50 percent, β is 2γ. To study the network's behavior under different loads, γ is varied as a parameter. Finally, we consider uniform and hotspot traffic with $h = 0.5$. Current values of service unavailability in SONET/synchronous digital hierarchy (SDH) networks refer to the life of services due to the fact that the provisioning process of establishing a wavelength service is very long and may involve many setup attempts. In the literature we find some proposed values for service unavailability in future IP/WDM networks with automated provisioning, ranging from 10^{-2} for bronze class of service [15] to 10^{-5} for higher-priority services. In this work we have not considered policies in the provisioning process, and therefore we may consider all lightpath requests as bronze. Therefore, from Fig. 5 it can be inferred that the GMPLS control plane of the ADRENALINE testbed is capable of performing automated provisioning of SPCs and SCs with service unavailability lower than 10^{-2} for $\gamma > 0.6$ (for SPC) and $\gamma > 0.85$ (for SC) when the total offered SC load is 50 percent of the total SPC, and $\gamma > 0.4$ (for SPC) and $\gamma > 0.45$ (for SC) when the total offered SC load is 10 percent of the total SPC load. From the picture it can be also inferred that the differences between uniform and hotspot traffic are minor as the load decreases. Therefore, we have taken a first step toward compliance with availability values suggested for future SLAs.

Figure 6 illustrates the end-to-end establishment delays of the ADRENALINE testbed considering the three main user access technologies (between users and optical managers), that is, ADSL, cable, and fiber. The delays in provisioning SPCs depicted in this figure, which are below 350 ms for user access with ADSL at 256 kb/s, prove that the collaboration among GMPLS, XML, and SNMP adopted in this work is of low complexity. Note that setting up SCs only involves the GMPLS control plane. For both SPC and SC requests the setup delay obtained in the GMPLS control plane is between 8–10 ms. The maximum (ring diameter) mean time for flooding an OSPF-TE update (e.g., link bandwidth) is performed in 146.3 ms; after that each node computes the route to any destination in less than 4 ms. In this work we have adopted SNMP and XML as management technologies to take the best of evolutionary and revolutionary approaches. The main strengths of SNMP are its simplicity, interoperability, and low footprint on agents, whereas XML enables the development of functionalities in line with the environment of future control-plane-enabled IP/WDM networks. As for the control

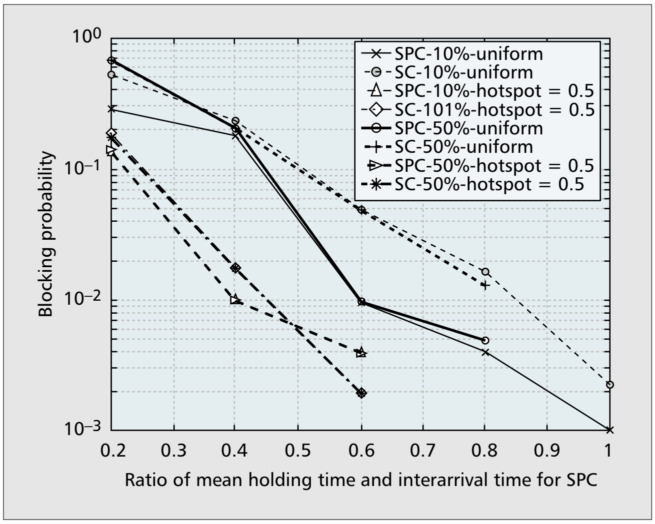

FIGURE 5. Blocking probability for SPC & SC.

plane, this work makes use of the GMPLS framework. SNMP and GMPLS have been integrated according to a complementary approach. With the experimental results obtained, we can add to this the fact that these three technologies have proven to be integrable and capable of assuring much lower values for the SLA parameter of connection establishment delay than those being suggested in the literature, which are of minute order [15].

CHALLENGES AND FUTURE WORK

In this section we take a look at remaining challenges in our proposed testbed, outline our envisaged solutions, and provide exciting avenues of future work on ADRENALINE. Clearly, one part of network management is performance monitoring and the related issues of network resilience, survivability, and availability. Conventional performance monitoring techniques typically require optical-electrical (OE) and electrical-optical (EO) conversion at monitoring sites in order to enable digital monitoring in the electrical domain. Given that ADRENALINE deploys all-optical node architectures, we are currently working on the implementation and testing of a *hybrid performance monitoring* system combining both digital and analog measurements of optical signals.

Furthermore, one of the most attractive challenges is to extend the existing signaling and routing protocols in order to propose and analyze different traffic engineering algorithms to be considered on different scenarios such as all-optical (transparent) or multiregion (i.e., multilayer). For the former environment, the aim of the proposed routing algorithms will be to provide computation of end-to-end optical circuit connections wherein neither OEO nor wavelength conversion are allowed. Hence, such routing algorithms should take into account both adequate signal quality and the wavelength continuity constraint. On the other hand, for a multiregion scenario, new routing algorithms will be studied to group higher switching layer traffic (e.g., IP) within the optical layer (i.e., grooming). We believe this will allow wavelength channel utilization to be improved as well as subwavelength granularity.

Network operators have become well accustomed to the fast timely recovery capabilities provided by SONET (SDH) automatic protection switching (APS) that can achieve service recovery within 50 ms after a fault event. Thus, enhanced network survivability must also be kept in future all-optical ring architectures. Although some might state that rings are special cases of meshes, technically speaking, the various intricacies of ring networks require special attention in the GMPLS framework. We will propose experimental enhancements to GMPLS fault management for optical multiplex and channel protection and restoration.

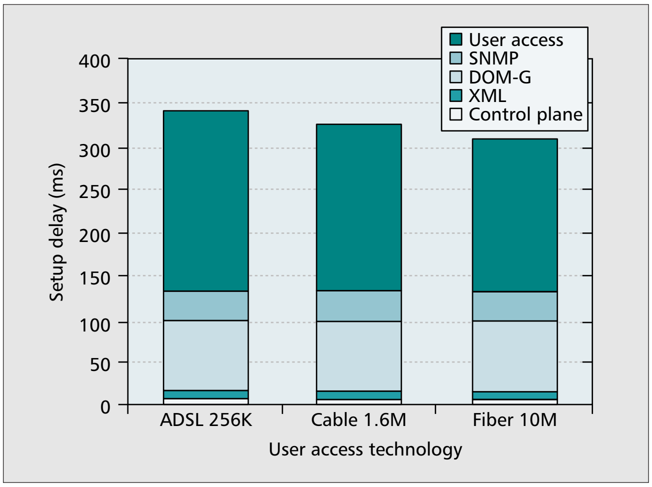

FIGURE 6. End-to-end setup delay for SPC.

CONCLUSIONS

This article has presented the architecture and implementation of the ADRENALINE testbed, an optical circuit-switched WDM testbed that deploys reconfigurable OADMs based on various technologies, such as arrayed waveguide gratings and tunable lasers. ADRENALINE combines both real and emulated optical nodes and DWDM links based on a distributed GMPLS-based control plane (RSVP-TE signaling for lightpath provisioning, and OSPF-TE routing for topology and optical resources dissemination), and a distributed management plane combining the industry standard SNMP with user-friendly XML-based tools to give users dynamic provisioning of lightpaths. In our experiments we have investigated user-driven (SPC) and equipment-driven (SC) optical connections, addressing their performance in terms of basic SLA parameters related to connection establishment (delay and availability) under several parameters. The results obtained in our testbed prove the feasibility of user management of lightpaths in an SLA compliance scenario in terms of delay and availability for future optical services, integrating GMPLS, XML, and SNMP technologies, and ensuring much lower values for the SLA parameter than those proposed in the current literature.

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BIOGRAPHIES

RAÜL MUÑOZ (raul.munoz@cttc.es) graduated in telecommunications engineering in 2001 and completed a Ph.D. degree in telecommunications in 2005, both from the Technical University of Catalonia (UPC, Barcelona). Since February 2002 he has been a research assistant in the Centre Tecnològic de Telecomunicacions de Catalunya's (CCTTC's) Optical Networking Area, participating in several Spanish and EU R&D projects in optical networking. Prior to joining CTTC he was an undergraduate researcher (TILAB, 2000–2001), research assistant (UPC's Optical Communications Group, 2001), and teaching assistant (UPC, 2001–2002).

CAROLINA PINART (carolina.pinart@cttc.es) has an M.S.E.E. (UPC, April 1999) and is a Ph.D. candidate at UPC (M.Phil., July 2004). She joined CTTC in 2001 as Director of Institutional Relations, collaborating with CTTC's Optical Networking Area. Prior to joining CTTC, she served as an undergraduate researcher (Siemens AG, Munich, 1998–1999) and consultant in technology (Altran, Paris, 1999–2001). Since 2000 she has participated in nine R&D projects in wireless and optical networking.

RICARDO MARTINEZ RIVERA (ricardo.martinez@cttc.es) is a graduate in telecommunications engineering from UPC (2002). He is currently pursuing his Ph.D. degree in the Department of Signal Theory and Communications at UPC under the supervision of Prof. Grabriel Junyent with a grant by CTTC within its Ph.D. fellowship program. Since May 2005 he is Research Assistant in CTTC's Optical Networking Area.

JORDI SORRIBES MEDINA (jordi.sorribes@cttc.es) is a graduate in telecommunications engineering from UPC (2003). Since September 2003 he is a Ph.D. candidate at UPC's Signal Theory and Communications Department and is pursing his thesis at CTTC under the supervision of Profs. Gabriel Junyent and Jaume Comellas. Since September 2002 he has been a UPC development engineer, working in CTTC's Optical Networking Area.

MARTIN MAIER (maier@ieee.org) was educated at Technical University Berlin, Germany, and received Dipl.-Ing. and Dr.-Ing. degrees (both with distinctions) in 1998 and 2003, respectively. Currently, he is a professor researcher at INRS, Montréal, CANADA, and focuses on evolutionary WDM upgrades of optical access and metro networks. Before joining INRS he was a research associate with CTTC, Barcelona, Spain. He is author of the book *Metropolitan Area WDM Networks — An AWG Based Approach* (Norwell, MA: Kluwer, 2003).

ABDELHAFID AMRANI (abdelhafid.amrani@meditel.ma) received a Ph.D. degree in telecommunication engineering from UPC. He is at Medi Telecom, Casablanca, Morocco. From January 2003 to March 2005 he was a research associate in CTTC. Prior to that he worked with the Optical Communications Group of UPC, where he was engaged in several R&D activities. Mainly, he participated in the European ACTS projects Mephisto and MOON.

GABRIEL JUNYENT GIRALT (junyent@tsc.upc.es) is a telecommunications engineer (Polytechnic University of Madrid, 1973), and holds a Ph.D. degree in communications (UPC, 1979, Barcelona). He has been a teaching assistant (UPC, 1973–1977), adjunct professor (UPC, 1977–1983), associate professor(UPC, 1983–1985), and professor (UPC, 1985–1989), and has been a full professor since 1989. In the last 15 years he has participated in more than 34 national and international R&D projects, and has published more than 30 journal papers and book chapters and 100 conference papers.

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