All-optical networks and switching technologies for a 3D videoconference system with the feeling of presence

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New ultra-low latency optical transmission and switching technologies are discussed in this paper. This work, carried out within the VISION project framework, sets the basis for building an ultra-low latency network for a high-quality videoconference system capable to provide a real feeling of presence, including 3D representation. The need of a full-optical transport network to achieve this aim is justified along the paper. The appropriate evolution of the switching techniques from optical circuit switching to optical packet switching is reasoned and the challenges hindering this evolution are stated. At a lower level, the technologies and materials available to perform optical switching, fulfilling the specific requirements, are reviewed. We present initial scalability simulations of electro-optic switches and future research in this field is posed. Finally, we propose and explain a design of a large optical packet switch employing optical labels.

1. Introduction

The need for high bandwidth is inherent to video data transmission. However, new generation videoconference systems will be far more demanding than current real-time video transmissions. A high-quality videoconference system capable of providing a real feeling of presence, including 3D representation, requires much more than a high capacity network. Briefly, such a system works as follows: a significant number of cameras capture the video images from different angles. Next, all the fluxes of data generated from the capture of video must be multiplexed with the capture of audio, also carried out from different positions. These audiovisual data have to be transported to the other end of the communication together with block matching and processing information [1].

It is not only the large volumes of data that must be transported which makes the design of the transport network challenging; videoconference applications, and specially such a quality demanding type, are extremely sensible to latency and jitter issues. Note, for instance, that video and data are coded and sent separately and thus a loss of synchronism at the receiver results in a low quality reproduction and spoils the feeling of presence. Some actual videoconferencing test results have proved that, to achieve a good performance, the end-to-end delay must be kept under 150 ms and the jitter, or variations in the delay, must be less than 20 ms [2]. Therefore, the goal when designing such a transport network is to achieve ultra-low latency, i.e. end-to-end latency practically equal to the propagation time, and to make jitter as small as possible.

In Section 2, the need for an all-optical network to fulfil these requirements is justified. Section 3 introduces the optical switching paradigms that mark the phases of VISION project. The switching mechanisms and technologies enabling those paradigms are reviewed in Section 4, and finally, conclusions are presented in Section 5.

2. The need for an optical network

Most of the currently deployed transport networks use optical technology just as a transmission medium, while the switching functions are performed in the electrical domain [3]. This fact underlies some limitations derived from the conversion of the optical signal to the electrical domain: a bottleneck arises in the intermediate nodes due to the practical limitation of electronics to 40 Gbps; on the other hand, conversions to the electrical domain themselves increase the complexity and cost of the nodes, and entail delays which penalize the end-to-end latency to an intolerable extent [4].

In the last decade, there has been a tendency to develop and implement the optical layer beyond its original transmission function. Ultra-low latency and high bandwidth features required for next-generation video communications can only be achieved by full-optical transport networks in which switching is performed in the optical domain [5]. Optical switching enables, in turn, the elimination of certain layers from the traditional model, IP/ATM/SDH/WDM. This model overloads networks with redundant information in the headers inserted at the different layers. It also leads to a higher complexity in equipment and control functions. The increasing penetration of optical technologies into network functions reduces costs and power consumption. On the other hand, it makes management and control plane implementation lighter: it enables models such as IP/Ethernet/WDM or IP (GMPLS)/WDM in which it is possible to conceive a unique distributed control plane [6].

3. Optical switching paradigms

3.1 Optical circuit switching – Phase A

Optical circuit switching (OCS) relies on the reservation of a fixed optical bandwidth, i.e. one or more wavelengths, to establish dedicated optical circuits over the network. The process consists of three phases: circuit set-up, data transmission, and circuit tear-down. One of the main characteristics of OCS is the two-way reservation process when setting up the circuit. This fact makes OCS suitable only for the cases in which the connection duration is long relative to the path set-up time. On the other hand, circuit switching results in low bandwidth utilization if the traffic to be supported is bursty [7]. In videoconference systems connections remain established for a relatively long time and the nature of the traffic is continuous, and hence this switching paradigm results a suitable choice. Phase A of our photonic network is based on the OCS paradigm.

In most of OCS current commercial implementations, optical circuits are permanent or semi-permanent. Nevertheless, bandwidth required in such a videoconference system is high and the number of wavelengths available in the network is limited. Consequently, our network should be provided with more intelligence and flexibility to reduce the overprovision of bandwidth and enable some QoS capabilities.

In VISION, an OCS network with the capability to provide bandwidth dynamically has been developed [8]. It is a meshed network with a distributed control plane based on GMPLS (Generalized Multi-protocol Label Switching) [9,10], as schematically represented in *Figure 1/a*, whose edge nodes have the building blocks depicted in *Figure 1/b*. This implies not only a better use of the available wavelengths, but also efficient and quick restoration of the services, the possibility of offering new services, as bandwidth on demand, and a range of traffic engineering mechanisms.

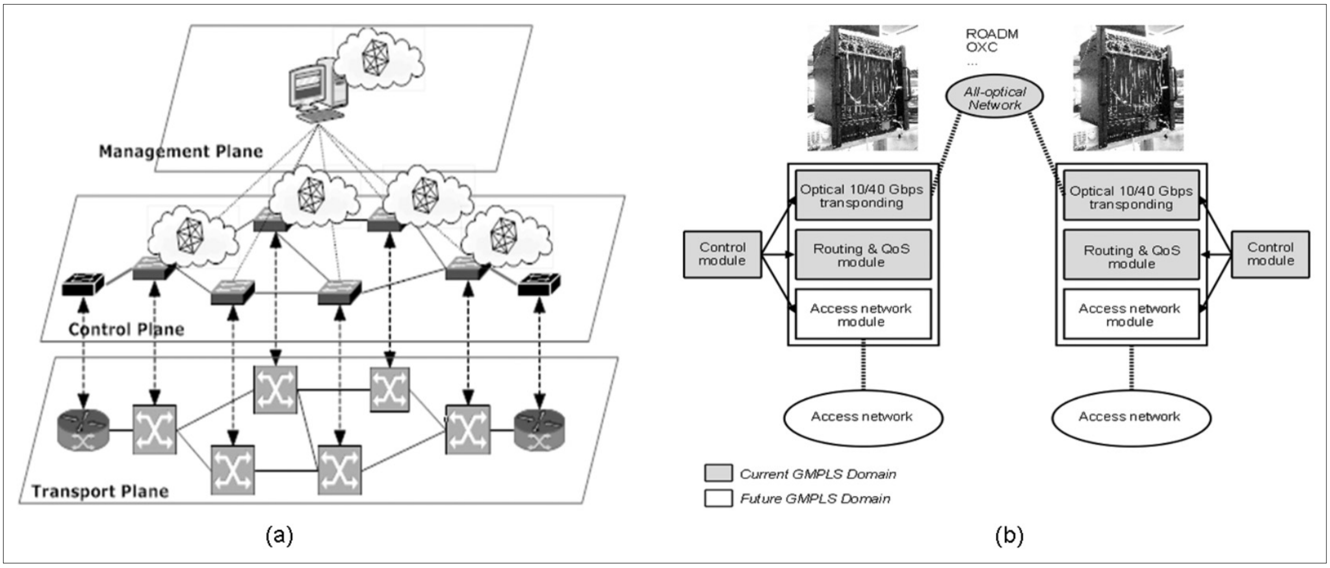
3.2 Optical burst switching – Phase B

Although OCS seems to be appropriate for providing enough bandwidth and low-latency for the targeted application, it is not cost-effective. A flexibility enhancement is required to adapt transport networks to the necessities of today's traffic [11]. Optical packet switching (OPS) is the paradigm we pursue. Nevertheless, significant advances in optical technology, both in switching mechanisms and buffering techniques, must be achieved before efficient OPS networks are made feasible. A medium-term approach is optical burst switching (OBS).

In the edge nodes of OBS networks, several optical packets are grouped into a burst. Once the burst is ready, a control packet is sent to "reserve" bandwidth and set switches along a path for transporting the data contained in the burst. The term reservation is not exact in this case, since the optical path that will be used it is not uniquely associated to a certain burst. There are several protocols to carry out the set-up process but all of them have common features: they use a one-way process, and more importantly, bursts can cut-through switches instead of being stored and then forwarded [7].

The one-way set-up process reduces vastly the set-up time relative to OCS. Burst lengths are generally of the order of tens of microseconds; hence switching times are required to be less than 1 μs, which is fast but realizable nowadays. However, the issues of how to deal with conflict situations and reduce burst drop-

Figure 1. Distributed control-plane based network: (a) network architecture and (b) edge nodes building blocks.



ping must be addressed. Optical buffering constitutes the ideal solution to retain the burst until the appropriate output is empty [12]. Nevertheless, this is not a requirement for OBS.

The design modularity of the network architecture developed in Phase A enables the gradual evolution to OBS. For instance, migration starts by introducing a fast optical cross-connect (OXC) instead of a millisecond range OXC.

However, the physical plane is not the only issue to consider in this evolution. The migration of the control plane from OCS to OBS is not trivial. Complexity grows tremendously, since optical packets are not sent anymore through predetermined dedicated circuits. Aspects like routing, signalling, or QoS, must be considered now for every burst and GMPLS is clearly dedicated to circuit management.

Many studies have dealt with the operation, architecture and signalling of OBS nodes, as in [13] or [14]. Nevertheless, OBS networks are still in an experimental stage. We are working on fast high-capacity switching matrices. Concerning the control plane, an effort is being done on adapting GMPLS to statistical multiplexing.

3.3 Optical packet switching – Phase C

Optical packet switching provides the highest degree of flexibility and efficiency to our network. However, there are some serious issues that complicate the deployment of an all-optical packet network and these are, as stated above, the practical realization of photonic buffers and the availability of ultra-fast optical switching matrices.

In OPS every optical packet is routed independently of the others. The packet has to be processed in every intermediate node in order to configure the switch. The packet header has to be analyzed while the payload needs to be temporarily stored in the optical domain. This store-and-forward way of switching entails the major problem of OPS, since it is not possible to buffer the light as it is done with electrical signals [15]. An approach for “buffering” light packets relays on employing coils of fibre to take advantage of the propagation delay, referred to as fibre delay lines. This solution is thorny and inflexible, since the fibre delay lines take up a lot of space and the propagation delay, and thus the storing time, is fixed. We focus our research in an exciting alternative: slow light devices. So far, some studies have claimed that intrinsic limitations will impede their use as buffers, as in [16]. However, some of the most recent works in this field [17-19] show promising results that indicate that it is just a matter of time these devices become a practical solution for optical buffering.

We have also considered the possibility of a “bufferless” optical packet network, e.g. employing wavelength conversion or the hot-potato or deflection algorithm, like in [20-22]. Regarding the reduced applicability of these techniques, we center our research upon slow light as a promising buffering approach to enable the evolution to OPS [23,24].

Photonic “buffering” is not the only issue in OPS. Even if storing light was made feasible, the optical switches must be incredibly fast. The switching times have to be small compared to the packet length. The transmission time of an IP packet at 40 Gbps can be between 10 ns and 300 ns depending on the length. Therefore, in order to avoid inefficiencies in utilization of the transmission channel, the switching time of the optical switch fabric needs to be around 1 ns or less [25]. The number of technologies capable to achieve this goal is even more limited than in OBS.

4. Optical switching mechanisms and materials

Optical switching operation typically occurs after a stimulus is applied. The stimulus is generated by a control module based on the analysis of signalling information, in the case of OCS and OBS, or based on the packet header, in the case of OPS [26]. Consequently, the design and optimization of an optical switch entails two separate blocks equally important: the optical switch fabric and the control processing part.

Several physical effects can unleash the switching operation in certain materials. In any case, the switching process influences the optical signal quality inserting losses, and other effects, such as polarization dependence and crosstalk, may occur. It also entails a switching delay that must be taken into account. Depending on the switching paradigm and on the size of the switch fabric, the upper limits regarding switching time and losses will vary. Therefore, the switching mechanism and the materials used to build a switching matrix must be chosen considering those particular restrictions.

4.1 Mechanical effect – MEMS

MEMS optical switches consist on a 2D or 3D matrix of micro-mirrors which connects the input fibres with the outputs.

They are a mature technology which presents some brilliant features, such as low insertion losses, low polarization dependent losses, and high cross-talk suppression. It is noticeable too that they enable cost-effective large switching matrices. However, taking into account our pursued evolution to OBS and OPS, we come across MEMS’ biggest limitation: the switching time. The switching speeds reported for MEMS have been in the range of a few microseconds to milliseconds [27-30]. Research has been done to reduce the angle through which light is bent and switching times of hundreds of nanoseconds have been achieved very recently [31]. These times are suitable for applications using permanent or semi-permanent circuits, and even burst switching in a future, according to the latest results. Nonetheless, faster alternatives must be considered for implementing packet switches.

4.2 Electro-optic effect

An electro-optic (EO) effect is a change in the optical properties of the material, generally the absorption or the refractive index (*n*), in response to an electrical field that varies slowly compared with the frequency of light. Pockels effect, particularly strong in ferroelectric materials, is the most relevant to build EO switches. It relies on the variation of n by applied electric fields.

The EO effect is very fast and therefore high-speed optical communication devices are expected to be realized exploiting it. As a consequence of the change of *n*, the signal phase is modified. Coupled waveguides or Mach-Zender interferometers (MZI) are simple ways to build a switch module based on the EO effect.

Amongst crystals available to develop these devices, lithium niobate ($LiNbO_3$) presents many winning points: it is a low-loss ferroelectric crystal with very fast response to the EO effect, 1 ns, and also a stable technology; fabrication techniques have been well established for this material, as single growth techniques and waveguide fabrication using Ti diffusion or proton exchange technologies [26]. Nevertheless, $LiNbO_3$ presents some drawbacks to take into account, as a high-driving voltage, polarization dependence and DC drift.

Other alternatives have been studied to build electro-optic switches based on different materials than lithium niobate. Lead zirconate titanate (PZT) is a ceramic material with a higher EO coefficient than $LiNbO_3$, which leads to a reduction of the driving voltage [32]. PZT is nearly polarization insensitive and it presents also low loss values. Unfortunately, it counts with some important limitations: it is incapable to match the fast response of $LiNbO_3$; the fabrication processes are complicated; and it is an expensive technology.

Polymers are a low-cost option for building electro-optic switches. Devices made out of polymers achieve the higher operation speeds. However, so far their losses are too high to build efficiently operative switches and they suffer from instability which can result in serious problems when performing the switching function [26].

We consider switches based on the EO effect as a promising alternative for the development of small switch fabrics in OBS and OPS networks, particularly due to their fast response. Our efforts are focused in solving their drawbacks, especially those related to their low scalability. *Figure 2* shows some illustrative results of the scalability simulations we have performed. An 8x8 EO switch was built from 2x2 lithium niobate MZI modules, following Spanke-Benes architecture. One can see how the amplitude of the optical field decreases as a consequence of the insertion losses introduced by every 2x2 module in the path from the input to the desired output waveguide. Losses of current commercial 2x2 $LiNbO_3$ switches are on the order of 5 dB, which certainly entails a problem when concatenating many of them. On the other hand, the residual amplitude observed in the rest of output waveguides is increased, leading to a degradation of the extinction relations.

It is noticeable, looking at the differences between *Figure 2/b* and *2/c*, how neither the losses nor the extinction relations are homogeneous. They depend on the path followed by the optical field. This fact complicates

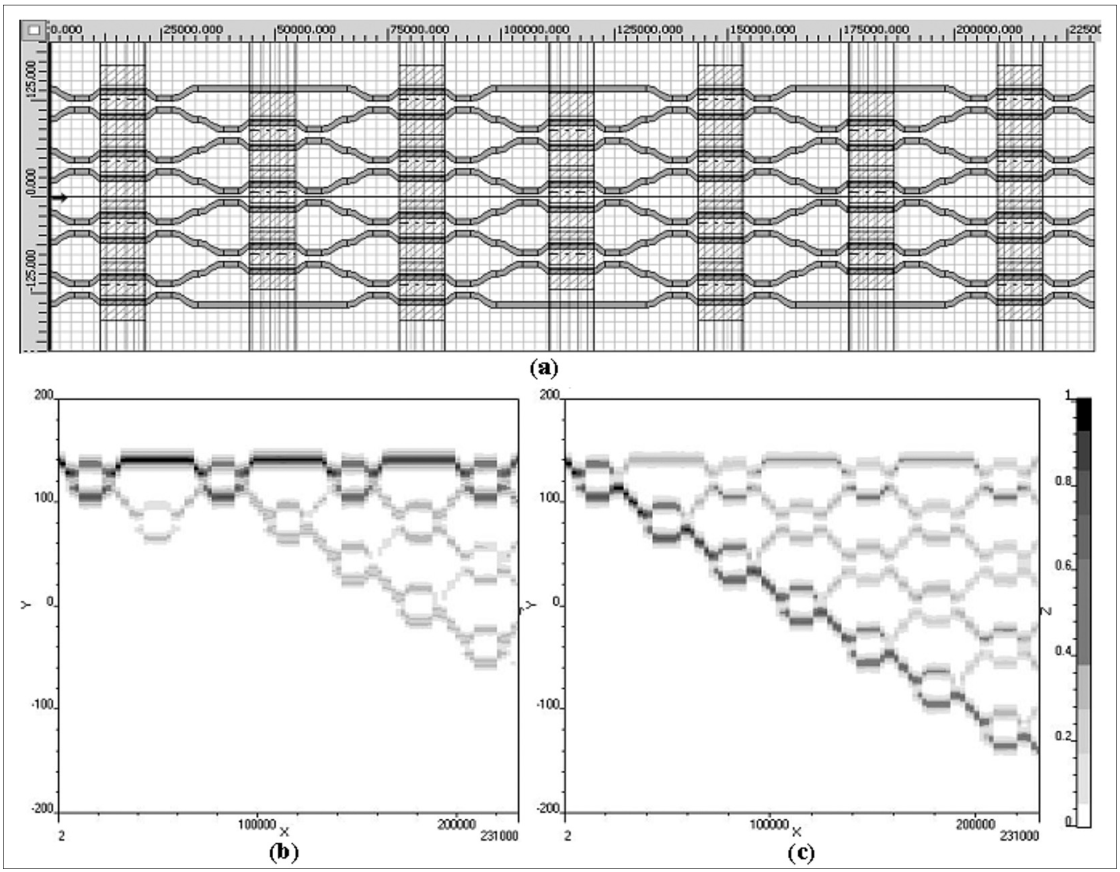


Figure 2.
8x8 lithium niobate electro-optic switch:
(a) layout, in units of microns
(b) XZ slice of the optical field amplitude for the shortest path
(c) for the longest path.

network design in aspects such as the gain equalization of optical amplifiers or the dynamic range of the receivers. Other architectures, such as Benes or Spanke, homogenize these parameters. However, they require waveguide crossovers, making it difficult to fabricate in integrated optics and leads to serious crosstalk issues.

The focus of our future research in this realm will be set on diminishing losses and improving extinction relation.

4.3 Semiconductor optical amplifier gain modulation

Semiconductor optical amplifiers (SOAs) are well-known and commercially available. They are essentially laser diodes without end mirrors, which have fibre attached to their ends. They are attractive to build all-optical logic gates. Instead of inserting losses, SOAs are able to provide gain to the propagating signals if they are correctly polarized. Moreover, they allow photonic integration due to their small size and inner structure.

A SOA can be used as an on-off switch by varying the bias voltage applied.

The gain of the SOA can also be optically modulated taking advantage of several nonlinear effects. For instance interferometric switches based on cross-phase modulation in combination with XGM in SOAs lead to an improvement of the extinction ratio [33].

The switching times of current switched SOAs are of the order of 100 ps. Much faster switching times can be achieved placing the SOA in a nonlinear loop mirror, and also employing two-photon absorption and free carrier absorption in combination with ultra-fast carrier cooling for the SOA recovery. These techniques achieve switching time faster than 1 ps, but they entail complications so far unsolvable [34].

The SOA-based switching techniques explained above constitute optical gates, i.e. 1x1 switches. To build larger optical switches, structures composed of couplers and SOAs are required, as shown in *Figure 3*. The fabrication of these structures results very expensive and hence just very small switch fabrics are expected to be built on the basis of SOA technologies.

4.4 Arrayed waveguide gratings

So far only MEMS-based switches were easily scalable to large switching matrices. Arrayed waveguide gratings (AWGs), also known as phased-array waveguide gratings, enable the realization of large optical switches with a single compact module.

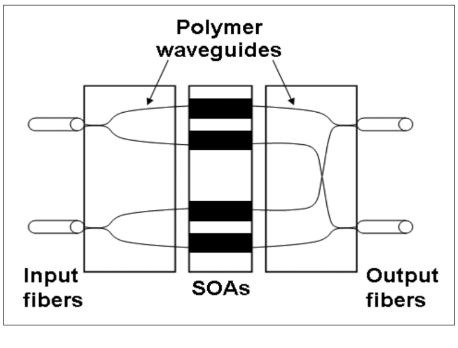


Figure 3. 2x2 hybrid SOA switch module

AWGs consist of two couplers connected by an array of waveguides whose different lengths are carefully chosen. They always route a certain incoming wavelength from a determined input to a determined output. To provide some control functionalities over the switch, reconfiguration properties must be added to the device.

Changing the input wavelength to the AWG in response to a control stimulus makes it possible to guide the signal to the desired output. Several research works have studied this type of solutions, e.g. the WASPNET (Wavelength Switched Packet NETworks) proposes an AWG-based optical packet switch using tuneable wavelength converters [35]. Tuneable lasers have also been considered for this purpose, as in [36], where wavelength accuracy and time stability is of outmost importance.

5. A proposed design for an optical packet switch

In *Figure 4* we propose an AWG-based optical packet switch. Control information will travel with the optical packet in the form of an optical label. Labels are processed and according to the stimulus generated by the control subsystem, buffers and label swappers are configured. No additional delay is introduced by the AWG and thence the switching operation time depends only on the label processing speed and on the switching time of the buffers and label swappers.

The electronic circuitry must perform the control functions within a range of time valid for OPS networks, of the order of 1 ns as stated in Section 2. This involves a big challenge for current electronics. The introduction of optical labels simplifies the electronic processing and thence contributes to the feasibility of OPS routers. Labels may also be processed optically in a future, which would reduce the requirements over optical buffering.

6. Conclusions

A 3D videoconference system with feeling of presence has strong requirements regarding latency, jitter, and bandwidth. These requirements can only be satisfied by an all-optical network.

An OCS based network with a GMPLS control plane has been implemented and current efforts are focused on enabling its evolution to OBS and OPS, both in the physical and control plane. Switching mechanisms have been discussed in this paper. Electro-optic switches represent a valid technology for OBS and OPS small switches. Other schemes, such as those including AWGs are required when talking of large fabrics.

We have presented a design for a large optical packet switch based on AWGs and label switching. Labels are capable of reducing control processing time and thus reduce the buffering requirements.

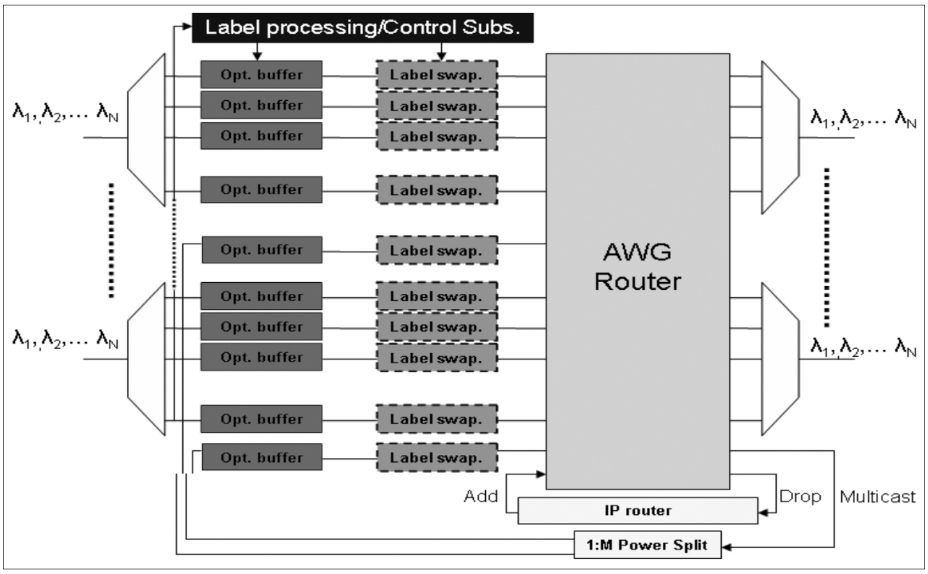


Figure 4. AWG-based optical packet switch

Along the VISION project we perform exhaustive research in two specific realms: electro-optic switches and photonic buffers. Hopefully, the results of our work will enable the realization of a practical optical packet switch and will contribute to the transition to OPS networks.

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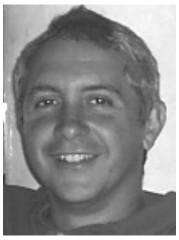

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