Optical Network Testbed—Key Enabler in Developing Current and Future Network Solutions

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***Abstract*—The all-optical network (AON) demonstrator is a trial system-level testbed for the validation and verification of key network building blocks, scalable architectures, as well as control and management solutions for next-generation wavelength division multiplexing (WDM) networks. Developed at the Communications Research Centre (CRC) in Ottawa, ON, Canada, the AON testbed has already validated certain system-level concepts at the physical and upper layers. The paper describes the crucial role of the AON testbed in research, development, and "proof of concept" for both emerging optical technologies at the physical layer (performance characterization) and customer-managed networks at the upper layer (network management). Moreover, it is expected that the AON testbed will continue to be a valuable playground for future developments of emerging technologies, solutions, and applications.**

***Index Terms*—All-optical networks (AONs), network management, optical network testbed, optical performance monitoring, user-controlled lightpath provisioning (UCLP).**

I. All-Optical Network (AON) Testbed as an Enabling Platform

THE all-optical network (AON) testbed is a long-term experimental network developed by the Communications Research Centre (CRC), Ottawa, ON, Canada, a federal government lab located in Ottawa, Canada. The testbed is a platform to verify and validate key physical-layer network building blocks, innovative architectures, applications, services, as well as control and management strategies for the dynamic provisioning of lightpaths over a wavelength division multiplexing (WDM) infrastructure. The current implementation of the AON testbed provides flexible connections over a transparent photonic-switched fabric for a typical metro environment, capable of transporting several wavelengths up to rates of 2.5 Gbit/s.

During the last couple of years, the AON testbed has been a key verification enabler of numerous research activities. In this paper, two developments, which both strongly relied on AON testbed capabilities, are presented. The first one deals with the role of the AON testbed in the evaluation of performance-monitoring strategies for the detection, identification, and localization of signal degradations [1]. It is based on real-time monitoring of key network parameters in the optical domain. In another example, the AON testbed serves as a vehicle for the trial development of a network-management strategy, based on peer-to-peer networking. A prototype of a network-management system was developed for customer-managed networks [7]. Each of these two developments, so tightly connected with the AON testbed, is to be elaborated on, with the AON testbed configuration described first.

Application activities related to the development of a dynamically reconfigurable optical layer are currently being planned and will require the use of the AON testbed for future challenging research activities.

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II. AON Testbed Configuration and System Specifications

An AON testbed was designed to serve as a vehicle to test and validate emerging technologies at the network platform system level, advanced network applications, protocols, and feasible network-control and management strategies [5]. Key network functionalities such as switching, transmission, amplification, attenuation, wavelength conversion, monitoring, multiplexing, and demultiplexing are incorporated into the testbed (Fig. 1). Each functionality deals with signals in the optical domain, hence, the AON designation.

Key building blocks of the AON testbed include: transmitter and receiver, photonic cross-connect, add/drop module (ADM), multiplexer (MUX), demultiplexer (DeMUX), optical amplifier, and variable optical attenuator (VOA). Monitoring points are placed at strategic locations in the AON testbed. Once transmitted, the signals remain in the optical domain while undergoing the following functions: switching, attenuation, multiplexing, amplification, equalization, etc. One channel is dedicated to the bit error rate tester (BERT) system. A pattern generator generates the sequence of ones and zeros in digital form that is then transmitted in the assigned channel of the AON testbed, and received and analyzed at the other end. This allows the evaluation of the quality of service (QoS) in the AON testbed.

The AON testbed was built to fulfill the following set of requirements:

1) transmission distance—20–200 km, typical for metro WDM applications;
2) four bidirectional channels (200-GHz spacing) at a maximum rate of 2.5 Gbit/s per channel;

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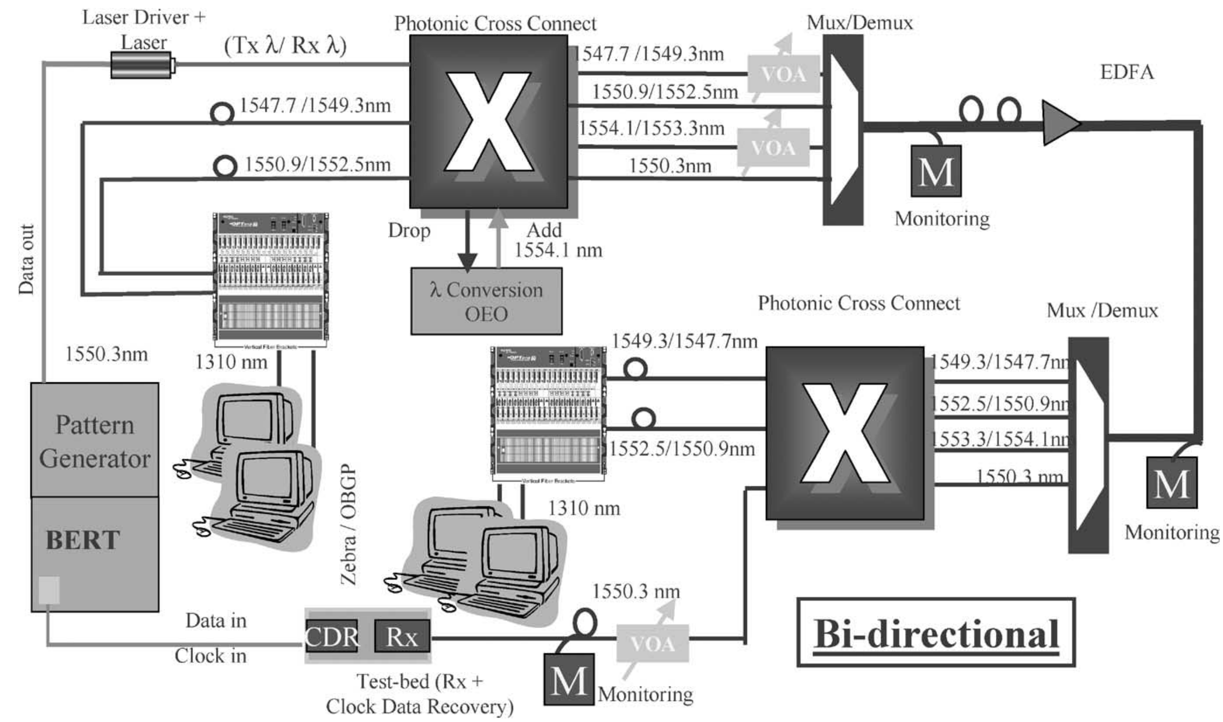

Fig. 1. All-optical network (AON) testbed.

3) optical functions—transmission, photonic switching, amplification, attenuation, multiplication, channel add/drop, system control, signal reception, BER testing, and optical performance monitoring per channel;
4) carrier system reliability—BER $\leq 10^{-12}$ ($Q \geq 7.5$ dB);
5) no signal regeneration along the transmission stage;
6) use of standard single-mode fiber (Corning SMF-28, loss of 0.2 dB/km);
7) signal power equalization before MUX and receiver.

Many research and development activities performed at CRC have relied on the AON testbed. In this paper, two of them are to be elaborated in more detail. The first one deals with the development of a performance-monitoring strategy for tracking optical signals with the purpose of detecting, identifying, and localizing signal degradations. The second one describes research efforts in developing a network-management strategy for peer-to-peer networking.

III. Optical-Signal Performance Assessment in a WDM Network

Communication systems continue to evolve towards higher data rates, increased wavelength densities, longer transmission distances, and more intelligence. Ever tighter monitoring of optical signals is of great importance for maintaining a high QoS [1], [2]. As technology innovations respond to a demanding higher degree of self-control, intelligence, and optimization for functions within next-generation networks, simultaneous real-time monitoring of all individual channels as well as quick and accurate measurements are inevitable. As monitoring becomes the crucial element of future dynamic and reconfigurable networks [2], some practical performance-monitoring strategies have been implemented and verified by using the AON testbed.

To characterize the critical parameters of each channel in our experimental WDM network, two bidirectional wavelengths were being transmitted between two network nodes within the AON testbed. Network monitoring devices, i.e., optical channel performance monitors (OCPMs), were placed at several strategic positions throughout the network, providing real-time feedback [3]. The OCPM's role is to observe channel presence and measure individual channel power (i.e., overall power distribution), optical-signal-to-noise ratio (OSNR) for each channel, and channel center wavelength position.

The OCPM is an integrated modular spectrometer device, operating at the physical layer, capable of simultaneously monitoring the performance of all individual WDM channels [4] in an optical domain. A fractional portion (1%) of the light power is tapped from the mainstream optical signal for monitoring purposes while keeping the properties of the main traffic unchanged. The tapped weak signal is then directed to the spectral element, from which the channelized wavelength components are separated in space. The spatially dispersed signals are detected by a series of detectors, where the optical signals are converted to electrical signals for processing. Supporting software was developed to track the real-time measurements, as shown in Fig. 2, with a less than 10-ms response time.

Based on the developed software, the following key optical parameters are monitored in real time: presence of channel, channel power, OSNR, and position of the wavelength [5]. There are also thresholds established for the last three monitored parameters. Upon exceeding the set thresholds, conditions requiring corrective action or immediate attention are automatically reported by e-mail or pager.

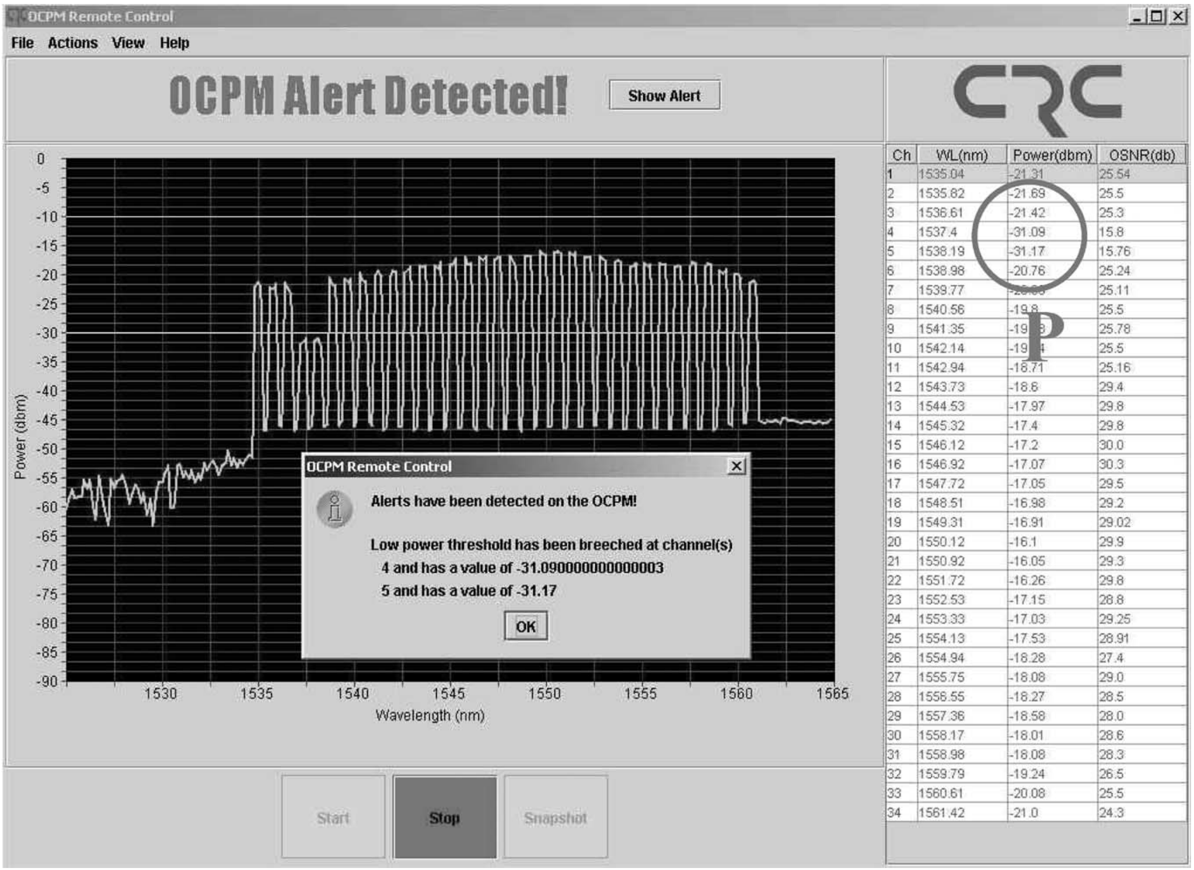

Fig. 2. Real-time monitoring of power, OSNR, and wavelength per channel.

Tests run within the AON testbed verified the importance of preventive simultaneous monitoring of all WDM channels. Distributed across the network, simultaneous monitoring allows detection, identification, and localization of faults and deviations from specifications in network, feedback to protection switching, or balancing the power due to the adding/dropping of the optical channels. Additionally, optical equipment degrades over time, so monitoring can be a key factor in the timely replacement of equipment. It is interesting to note that industry has fully accepted the proposed strategy as one that can successfully meet network requirements for monitoring and maintaining a high network QoS.

The example explained above, featuring optical signal performance assessment in a WDM network, has demonstrated the AON testbed ability to provide thorough network-type research and developments with a huge impact on complex network applications within a relatively simplified testbed environment.

IV. Network-Level Control and Management

In addition to providing high-bandwidth point-to-point transmission capabilities, WDM technology enables the dynamic setup of end-to-end lightpaths. This new function fundamentally changed the operation of transport networks. Conventionally, end-to-end lightpaths were statically provisioned by manual management approaches, which could take from days to weeks to accomplish a provisioning process. Now, photonic components and equipment can be dynamically configured in seconds or less. Thus, control and management at the network level became the bottleneck for fast real-time lightpath provisioning.

The network-level control and management are to coordinate the operation and configuration of individual network elements. The coordination should be achieved with minimal human-operator intervention, preferably by automatic processes, with the support of software control protocols or management systems.

In general, the challenges for the network-level control and management lay in two major aspects: scalability and interoperability. Many seemingly simple control methods for individual components or equipment do not apply for large-scale networks, because when the number of those components or equipment increases, the complexity of the control methods may increase dramatically. For example, although it is simple to find a path between a pair of switches for a network with only a few switches, to find a path in a network with hundreds of switches is challenging. If a routing algorithm is not scalable, its complexity for finding a path in such a large network may explode beyond a manageable level.

The interoperability is of importance because a network may consist of elements from several vendors, and a network needs to communicate with other networks made of different types of elements. Significant research has been conducted to specify standards for the control plane of optical networks.

Generalized multiprotocol label switching (GMPLS) and optical user–network interface (O-UNI) are examples of many successfully defined standards. However, since the requirements and functions are evolving, existing standards need to be constantly extended. Emerging protocols suffer from interoperability issues and tend to experience a very slow standardization process. Although the interdomain control plane is making progress [6], it is still in its infancy.

Management approaches are complimentary to the control plane for AONs. More advanced features may be quickly implemented in management systems before standards are defined. For small- to medium-size networks, management approaches may offer sufficient real-time performance and scalability compared to the control-plane solution. We have been motivated to achieve customer-controlled lightpath provisioning by building a new management system, which supports both intra- and interdomain applications.

At the present time, customers build their transport networks in various ways for metro and intercity connections [7]. In metropolitan areas, customers may acquire their own dark fibers. They may also participate in so-called "condominium" dark-fiber networks to better manage their connectivity and bandwidth. They light up the fibers with their own equipment and interconnect their fibers to other institutions, commercial service providers, or Internet exchange points. For long-distance transport networks, many providers are selling or leasing point-to-point wavelength or synchronous optical network (SONET) channels. Some providers are offering "condominium" wavelength solutions, where a number of customers share the capital costs of deploying long-haul optical networks. In return, each customer in the condominium consortium owns a set of wavelength channels.

Potential customers of provider-owned and provider-managed optical networks are motivated to build their own transport networks as a new alternative since they perceive some new benefits [8]. First of all, in customer-owned optical networks, the cost of bandwidth is substantially reduced, as it now largely becomes a capital cost rather than an ongoing monthly service charge. Customers have more flexibility in network planning and deployment and are able to negotiate the best deal from different suppliers. They may lease or purchase network resources from a number of independent suppliers, as well as participate in condominium networks for part of their network. Secondly, Internet costs are reduced by remote peering and transit. Customers manage their peering relationships without having to contact a central management body or pay expensive Internet transit fees. Thirdly, since customers directly own and manage the optical network, the bandwidth and QoS are guaranteed. The complexity of service management at the IP layer is removed.

Associated with these new benefits of customer-owned networks are some new management challenges. The first challenge is the management of network resources from different sources. In this new network architecture, only the customer has the total visibility of its own network, as no provider can see all the network elements. The second challenge is the collaboration among multiple independent customers without coordination through centralized management. Customer-managed networks adopt the peer-to-peer architecture, in which customers peer with each other [9]. The third challenge is the dynamic partitioning of a provider's resource to customers.

A user-controlled lightpath provisioning (UCLP) system was designed to address these management challenges for customer-owned and customer-managed optical networks, under a CANARIE-funded directed research program [7], jointly with the University of Ottawa and later with collaboration from University Polytechnics of Catalonia (UPC). The UCLP system has been tested on CANARIE's ONS lab and deployed on CA*net 4, which is the Canadian Research and Innovation Network [10]. The UCLP system is based on Sun Microsystem's Jini and JavaSpaces technology (Fig. 3). An interface to grid applications is provided so that grid applications may access the system to dynamically establish high-bandwidth lightpaths.

Recently, an international connection was successfully established using an interim release of the UCLP system [11]. Fig. 4 illustrates the setup of the demonstration. Two sets of UCLP systems were installed to control CA*net 4 and i2CAT [12], respectively. An MPLS tunnel was manually configured in between. UCLP systems dynamically set up two segments of lightpaths to the MPLS tunnel, which was represented as a virtual switch and acted as a peering point. High-quality videos were transmitted over the dedicated connection from Barcelona, Spain, to Ottawa, ON, Canada.

V. Future Program Involving AON Testbed

The AON testbed will play a key role in future research activities. One of them, currently in the planning phase, is regarding the development of a dynamic reconfigurable optical layer. That program will involve the implementation of a reconfigurable optical add/drop MUX in the AON, and down the road, the development of an interface between the physical and control layers for tracking the performance of each wavelength in a WDM network. The proposed research requires intensive network validation and verification. Moreover, the plan is to evaluate these concepts by connecting the AON testbed with Canada's Research and Innovation Network, for the demonstration of wavelength services over CA*net 4.

The concept of UCLP is evolving. More new concepts and features will be added to the second version of our UCLP system. In the future, we will address the inter-UCLP communications to exchange information for UCLP systems in different management domains. We plan to enhance the UCLP system to make it web services resource framework (WSRF) compliant [13].

VI. Conclusion

CRC has been successfully operating trials under its AON demonstrator program for the last couple of years. Over that time, the AON testbed continues to be a proof-of-concept vehicle for verifying and validating key physical-layer network building blocks, innovative architectures, and management strategies for the dynamic provisioning of lightpaths over a WDM infrastructure.

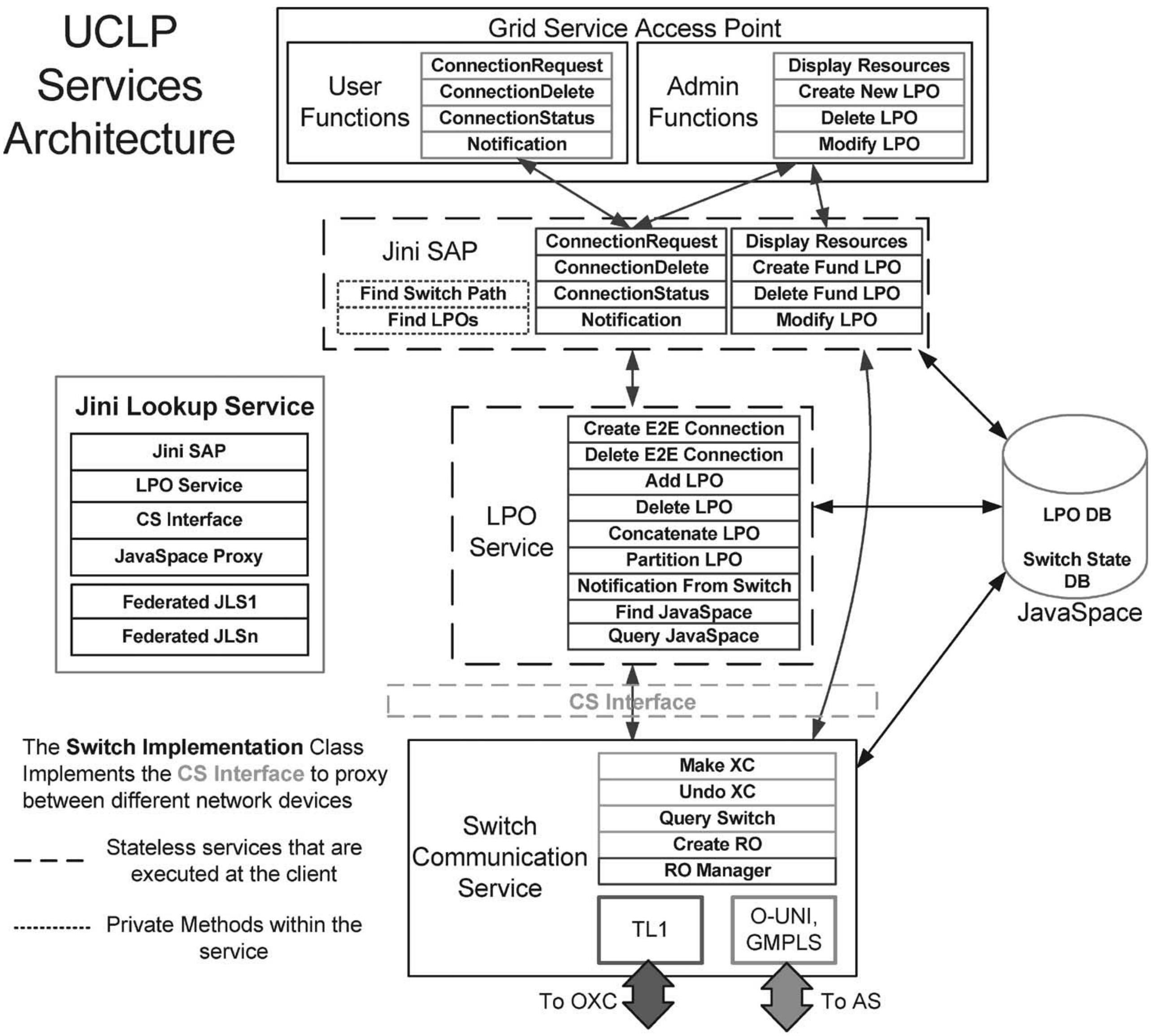

Fig. 3. Overview of UCLP system architecture.

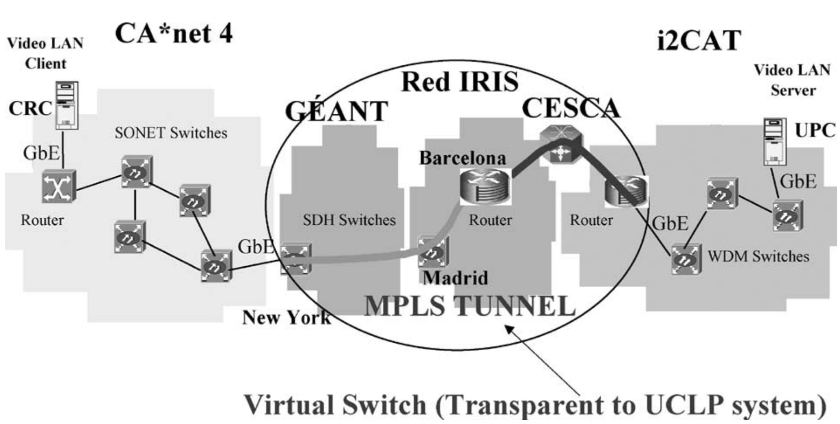

Fig. 4. Network configuration for using UCLP systems to dynamically establish a connection.

Performance-monitoring techniques have been discussed within both the research and industry communities and they are starting to get industrywide acceptance. Some companies have already expressed an interest in a collaborative initiative in that field with CRC. As a result of another activity, CRC leads an initiative to connect its facility with three others facilities (Carleton University, University of Ottawa, and National Research Council) through the National Capital Institute of Telecommunications (NCIT) network. Numerical modeling was used to analyze the WDM transmission links, focusing on the characterization of signal degradation levels, optimization of the power link budget, and end-to-end physical connection [14].

Our UCLP system has proven some innovative ideas to build a management system for UCLP. Moreover, the prototype of a network-management system for customer-managed networks has been deployed in the CA*net 4 network and other international National Research and Education Networks (NRENs).

New features will be continuously added to the AON testbed. The research on network-level optimization will provide design and planning methods and tools for large-scale networks.

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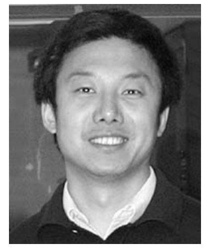

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