Report of "US/EU Workshop on Key Issues and Grand Challenges in Optical Networking"

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Executive Summary

Workshop Overview

This Workshop was jointly sponsored by the National Science Foundation (NSF) and the European Union (EU) (ePHOTON/One and COST). It was held June 27-28, 2005, at the European Commission (EC) premises in Brussels. Workshop participants included a diverse set of international experts from the optical networking research community in the US and the EU. (A delegation of ten optical networking experts from Japan was also invited to the Workshop as observers.) The Workshop objectives were: (a) to determine the future research needs and opportunities in optical networking, and (b) explore and define methods to facilitate stronger research collaboration between US and EU researchers.

Attendance at the Workshop was by invitation only, and limited to 30 participants -- 15 from US and 15 from EU. A Technical Program Committee (TPC) determined the Workshop's Technical Program.

Technical topics covered at the Workshop included (1) optical network **architectures**; (2) experimental optical systems research (i.e., **hardware** systems); and (3) optical network control and management (i.e., **software** systems). Special attention was paid to collaborations between these areas, to address forward-looking and high-impact research.

There was a consensus that successful and high-impact research in optical networking can be achieved by incorporating expertise from these diverse disciplines, and is referred to here as "cross-layer design". In this regard, roughly three layers can be identified: (1) the application layer at the top (including control and management software); (2) the network architecture layer in the middle, and (3) the physical (or optical communications) layer at the bottom (mapping with the three topics--software, architecture, and hardware--indicated above).

This Workshop Report details important research challenges, both fundamental and technological, which are likely to be at the forefront of this field for many years to come. The remainder of this executive summary contains the technical recommendations from the workshop. The executive summary is followed by three appendices, which provide detailed discussions on the three technical topics: (1) optical network **architectures**; (2) experimental optical systems research (i.e., **hardware** systems); and (3) optical network control and management (i.e., **software** systems). Finally, the Workshop Agenda and the List of Participants are also attached.

Technical Recommendations

Internet-Driven Architectures.

In today's data networks (e.g., IP network), two edge devices, e.g., interfaces of two IP routers, are interconnected by a leased line (namely a circuit of fixed bandwidth) with a long holding time, perhaps based on an annual lease. Using emerging optical networking architectures, particularly control-plane software and optical switches, such IP routers (and other edge devices) should be able to "dial for bandwidth" on an as-needed basis, just like humans can pick up the phone and dial anyone around the world. The holding time for such a "virtual" link between the edge devices can be of any duration: from a few seconds to months, as need be. Also, the capacity of such a bandwidth pipe can range from that of an optical wavelength channel (which is OC-192, 10 Gbps, today and expected to increase to OC-768, 40 Gbps, soon) to sub-wavelength granularity.

What architectural solutions should be developed to efficiently "groom" (i.e., pack, unpack, and switch at intermediate nodes) sub-wavelength granularity connections of diverse bandwidth (including IP flows, multi-protocol label switching (MPLS) tunnels, etc.) on to high-capacity wavelength channels in an optical network? What are the corresponding important research problems in (1) traffic engineering ("put the *traffic* where the *bandwidth* is"), (2) network engineering ("put the *bandwidth* where the *traffic* is"), and network planning ("put the bandwidth where the traffic is *forecasted to be*"). While network planning, and traffic engineering to a lesser extent have received research attention, the important problem of network engineering needs more research investments, e.g., models to understand this problem and methods to calculate "exhaustion probabilities" (to determine when will the current network resources be exhausted, and more capacity needs to be added, under increasing traffic intensities).

Application-Driven Architectures.

Many emerging applications in large-scale science communities require that geographically-distributed devices be connected by high-bandwidth pipes (with quickly-reconfigurable capacities). The embedding of such a set of bandwidth pipes is synonymous to the creation of a virtual private network (VPN), and is referred to as a **"Lambda Grid"**.[1] This virtualization is possible because the optical network actually consists of multiple levels. At the lowest level, we have the topology of the fiber layout: fiber is laid in bundles, so by splicing together fiber strands in different bundles, long fiber links can be created. The collection of such fiber links forms the physical fiber-link topology, which is embedded on the fiber-bundle topology. Noting that each fiber strand can support many wavelengths (160 today), an additional level of virtualization can be performed, by considering wavelength-paths, called *lightpaths*, on the fiber-link topology. Working recursively, and noting that the capacity of a wavelength can also be sliced up in the time domain, one can create powerful multi-level network architectures to suit the appropriate sets of networking applications and their needs.

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[1] In a non-optical-networking context, this is generally referred to as the **Grid** problem, (1) where the concern is not on how the bandwidth pipes between edge devices are set up and maintained (and they could be based on current IP networks--i.e., non-optical networks--also, and (2) where the focus is mainly on middleware to map the Grid to the application's needs. Thus, the **"Lambda Grid"** problem has very much to do with optical networking, which is not the main focus of the Grid problem.

The corresponding research problems in multi-level networks, in general, and Lambda Grids, in particular, need to be identified and attacked. It should be recognized that the Grid idea has two very significant research components: one on middleware and another on the optical networking, namely on "Lambda Grid". The "Lambda Grid" is very appropriate for the optical networking research agenda of the US National Science Foundation's Networking Technology and Systems (NeTS) Research Program.

Another application-driven network architecture research problem is to exploit the multicast feature of emerging optical switches and the potential for supporting one-to-many, many-to-one, and many-to-many applications at low cost. What sorts of possibly-new optical hardware can support such multicast-capable switching devices? How can "light-trees" (which are multicast extensions of lightpaths) be set up to facilitate the above applications efficiently?

Hierarchical Network Architectures (Bringing Access to the Backbone).
Traditionally, research and development in optical networking (and in networking in general) has focused on the backbone (or long-haul) network. However, it is well known that the access network is a major bottleneck because more end-users want higher-capacity bandwidth pipes to their homes and businesses at low cost. The US is significantly behind other countries, particularly Korea and Japan, on optical access network R&D. This situation ought to be rectified with significant new R&D investment in the optical access area.

Some attractive options for broadband optical access include passive optical networks (PONs), wavelength-division-multiplexing PONs (WDM-PONs), free-space optical access, WDM optical LANs and bus architectures, etc. What are the corresponding network architectures that are scalable (to grow by orders of magnitude to eventually support 1 Gbps (and beyond) per end user for all users), flexible/efficient (in terms of instantaneous bandwidth allocations), fair (to all users as well as to service providers who compete for their customers over the same access network infrastructure), cost-effective, and allow the development of new unanticipated services? What are the corresponding new breakthroughs needed in optical hardware technologies to recognize this vision? What are the efficient interconnection methods between such future broadband access networks and metro and backbone networks?

Hybrid Optical/Wireless Access Networks.
While fiber to the home (FTTH) is the ultimate goal for many people, it is also expected to be a costly and possibly an impractical solution for many geographically-challenging areas. On the other hand, wireless access is easily deployable because it does not require much infrastructure, but its capacity, robustness, and coverage area are limited.

Thus, future access networks could potentially employ "fiber as far as possible" from the telecom switching station towards the user, and then have wireless "take over". The "wireless portion" could also employ multi-hop routing principles, which can also lead to better robustness properties against optical fiber failures. There are excellent optimization problems as follows: (1) What is the distance (or "sweet spot" up to which fiber should be the carrier before wireless takes over? (2) How can the wireless part of the network "self-organize" itself (w.r.t. the corresponding multi-hop mesh topology, routing and load balancing, etc.), particularly while working in conjunction with the optical part? (3) if an optical trunk fails, what methods can direct the traffic away from the failed fiber to other parts of the network automatically? Such problems require research investments.

Robust Network Architectures.

Optical networks are the ultimate solution for robust networking in general: fiber is the best tunnel to secure the current Internet traffic. Future networks will undoubtedly deploy optical network technologies to increase robustness and the question arises how to design optical networks to quickly recover from such failures because of the huge amount of data loss it can potentially suffer.

To facilitate robust network design, both proactive and reactive methods should be investigated, where proactive methods pre-plan some of the recovery methods in advance such as setting aside backup routes, sharing backup capacity with other paths' backup capacity, setting up backup routes only (but not necessarily backup bandwidth), etc. Noting that different users may have different needs, and also that different parts of a network may have different failure characteristics, differentiated survivability methods need to be investigated. Traditionally, the notion of network service has been "binary", i.e., it is either available (as contracted) or not. But the notion of "degraded service" should be developed, i.e., even if some parts of the network are down, service can still be provided at a reduced level, if possible. How to deal with large-scale network disasters should be developed so that, again, if some parts of the network are working, they should be able to support as much of the services as possible. Research on large-scale correlated failures (or attacks) should be encouraged. The correlation between survivable network architectures and network security should also be studied. The interplay between overloads, faults, and attacks needs investigation as well.

Holistic Design.

Optical networking, just like wireless networking, is a highly interdisciplinary research area. It requires sound knowledge on a very diverse set of disciplines: from communications to optics to electronics to computer architecture to algorithms to network protocols to operations research to telecom business models. Traditionally, in optical networking, most of the emphasis has been put in the (bottom-most) optical layer only in the past; however, history has taught us that, without sound architectures, applications, and economic models in mind, one can produce technologies with limited or no usefulness. Thus, the future optical network should not be designed bottom up; neither should it be a top-down design in which case the applications and network architecture layers operate in isolation from the physical layer. Instead, the network should be based on a "push-pull" design where all three layers work together harmoniously. Such holistic (or cross-layer design) problems should be encouraged.

An excellent example of "holistic design" is "impairment-aware routing" where an application needs a service path of certain properties through the optical network. Can the network architecture layer work with the physical layer to determine if one or more such good-quality paths exist and allocate one such path to the application to meet its needs? Also, in a transparent all-optical wavelength-routed network, where should regenerators be placed optimally (to minimize network cost) so that all necessary lightpaths can be set up with appropriate signal quality? How can optical orthogonal codes be used for efficient routing purposes in an optical backbone mesh network? How can quantum cryptography be used to satisfy the security and other needs of various applications?

Hardware Acceleration.

In an optical network, the optical layer is responsible for providing the optical transmission and optical switching functionalities. While optical transmission is quite mature today, optical switching is not, despite billions of dollars of investment by the industry. This is because of lack of attention to the "holistic design" principles stated earlier. The optical switching platforms which we have today are primarily based on O-E-O (optical-electrical-optical) approaches, where electronics in the data path is employed for signal shaping, performance monitoring, etc.

As a community, we ought to continue to invest in all-optical switching because of the various advantages (e.g., transparency) that it brings, such as development of 3R regeneration, all-optical wavelength conversion, optical memory, etc. But this sort of investment should be made in a "cross-layer-design effort". Other forms of hardware accelerations which can lead to more integration of functionality and reduce the optical hardware footprint, power consumption, and cost, should be encouraged, such as photonic integrated circuits, optical backplanes, etc.

International Collaboration.

Given that the US and EU are powerful economies with strong track records in optical networking research, it makes most sense for these two communities to join forces to enable their respective researchers to collaborate with one another to produce higher-impact research. Furthermore, the collaborations for education, that has to come hand-in-hand with research, are the necessary steps in that direction. The examples discussed were the development of virtual departments, joint curricula and student and teacher mobility. Currently, the international collaborations are possible on a very small scale, e.g., individual US researchers can join a EU project at no cost.

Therefore, the US and EU government organizations are strongly encouraged to give this matter strong consideration to facilitate stronger ties between our two communities in the area of optical networking. The e-Photon/ONe will be funded by the European Commission for two additional years (until the beginning of 2008). After the meeting in Brussels, their project officer strongly recommended to formally include some US partners into the project. They are currently seeking our advice and opinion on more-suitable and more-effective ways of implementing scientific interactions across the ocean.

Appendix A:

Research Issues in Optical Network Architectures

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A.1 Network Architectures

Networks have evolved to support the following three architectural paradigms:

1. Connection-oriented, circuit-switched like the SONET/SDH network or telephone network where point-to-point links are created.
2. Connectionless, packet-switched like Internet Protocol (IP) routing based architecture.
3. Connection-oriented, packet-switched like Asynchronous Transfer Mode (ATM).

The issues involved in optical network architectures may be different from the issues observed in conventional wired or wireless counterparts due to the limitations and/or new enhancements available in optical technologies. As optical technologies continue to progress rapidly, the optical network architectures have evolved into the three different generations as explained below.

A.1.1 Optical Networking Generations

Historically speaking, optical networking can be roughly classified into three generations. The first generation used point-to-point optical connections. The second generation used the connection-oriented optical circuit-switched paradigm. The third generation is a proposal to mix and match packet and circuit based optical architectures to provide maximal flexibility and to exploit the best features of both the electronic and optical domains. A brief overview of the characteristics of these three generations of architectures is given below.

- *First Generation:* In the first generation, transmission links are operated in the optical domain. However, the switching, cross-connecting, multiplexing, and regeneration functions are implemented in the electronic domain. Examples include Plesiochronous Digital Hierarchy (PDH), Synchronous Optical Network/Synchronous Digital Hierarchy (SONET/SDH), Passive Optical Network (PON), and various networks using optical links with Internet Protocol (IP) routers, Gigabit Ethernet (GbE), and 10GbE switches.
- *Second Generation:* The optical transmission links of first generation are enhanced with other functionalities such as regeneration, amplification, cross-connection/switching, multiplexing, adding and dropping of signals, all in the optical domain. They allow optical circuits to pass through multiple intermediate optical links without any electronic signal processing. However, control and management functions are still performed electronically. Networks with Wavelength-Division Multiplexing (WDM) on their

transmission links, WDM-based Optical Add/Drop Multiplexers (OADMs), all-optical crossconnects (OXCs), and Broadcast-and-Select networks belong to this generation.

- *Third Generation:* This includes optical network architectures that propose to use Optical Packet Switches (OPS) and Optical Burst Switches (OBS) where payloads are handled in the optical domain and packet headers in OPS and control signals in OBS are handled in the electrical or in future in the optical domain. In such architectures, packets are queued in optical delay lines (memory buffers) to enable timely processing and to avoid contention. With such packet switches, both connection-oriented and connectionless networks can be created. To fully realize this generation of optical networks, we still require significant enhancements in optical technologies, particularly in optical signal processing, optical memory and optical logic.

Given the above classification of the three generations, all three types of network architectures are possible for optical networks. Important aspects at the data plane level are: amplifiers, fixed or tunable lasers, continuous- or burst-mode receivers, optical add/drop multiplexers, crossconnects, optical burst switches, and optical packet switches. A key component is an optical (3R) regenerator, which would enable a decoupling between the design of transmission links and the design of switching and network architectures, as is the case today for first-generation optical networks and for electronic networks. A data plane realized using these components requires either an electronic or an optical control-plane entity such as a signaling/routing engine at each OADM, OXC, OBS, or OPS switch. Implementation of these control-plane engines in the optical domain requires further advances in optical processing technologies. Finally, management-plane entities that typically involve much more significant computing can be expected to rely on electronic implementations in the near future.

A.2 Emerging Trends and Requirements

A.2.1 Increasing Access Speeds

Recent innovations in network components and technologies enable new and advanced network architectures and capabilities. These innovations include the great increase in per-fiber capacity enabled by dense WDM (DWDM) systems, ability to provision dedicated network resources in a dynamic fashion, development of network nodes with increasing capacity for switching/routing of data, and ready availability of 10 Gbps router, switch, and client interface cards (note that 10 Gbps transmission requires fiber as a medium). This enables the technologies in the core (backbone) to gradually migrate towards the access (edge). The likelihood is that these network technologies will not only enable new and advanced network architectures, but they will demand such new architectures. In particular, with the advent of inexpensive 10 Gbps client network interface cards (NICs) and PC busses with adequate capacity, many end systems will soon have capacity on the same order of magnitude, or beyond, as that found on a single router or switch backbone links. This situation will require network architectures which can provide for innovative and dynamic use of the optical network and transport systems to facilitate the intelligent handling and management of user data flows. Fully exploiting advanced capabilities inherent in technologies such as SONET/SDH, DWDM, and Ethernet virtual local-area networks (VLANs) will be required to support future network and user requirements.

Ultra-broadband access to the home or small-business user is still a problem as the last-mile pathway is still extremely narrow. Cable- and Digital Subscriber Line (DSL)-based Internet access only provide bandwidths of the order of a few hundred kbps to several tens of Mbps while optical pipes are operating at tens of Gbps. Such a mismatch in capacities between the core and last-mile has resulted in minuscule returns on heavy investments. A clear strategy is needed for widening the last-mile pathway and ensuring that a significant fraction of the huge core capacity is revenue bearing. Interestingly, concurrent with the capacity expansion in the core, there has been an increase in desktop data-generation rates and in in-home networks' capacities. Today's desktops and laptops are capable of generating data at rates of several hundred Mbps to a few Gbps that may need to be sent over a network. Correspondingly, the introduction of IEEE 802.11b and 802.11g has increased in-home network capacity to 11 Mbps and 54 Mbps, respectively. Thus the last mile is lagging far behind.

One possible solution to the last-mile capacity problem is to extend fiber to the home (FTTH), or at least to the curb (FTTC). Such solutions have many attractive features including seamless integration with fiber-based metro-area and wide-area networks (MANs and WANs). We also need to recognize the role of Ethernet-based optical access networks. There needs to be a clear solution that will provide an evolution path for access that will be upgradeable and scalable as more and more users are directly connected to the backbone using high-speed access.

While fiber to the home (FTTH) is the ultimate goal for many people, it is also expected to be a costly and, for many geographically-challenging areas, possibly an impractical solution. On the other hand, wireless access is easily deployable because it does not require much infrastructure, but its capacity, robustness, and coverage area are limited. Thus, future access networks could potentially employ "fiber as far as possible" from the telecom switching station towards the user, and then have wireless "take over". The "wireless portion" could also employ multi-hop routing principles, which can also lead to better robustness properties against optical fiber failures. Such problems require research investments.

A.2.2 Migration Towards Mesh Topologies

There appears to be an increasing trend towards supporting arbitrary (mesh) topologies instead of ring, star or bus topologies normally deployed in today's metro- and wide-area networks. This trend is most likely based on the success of arbitrary-topology IP networks in enterprise, metro- , and wide-area networks.

Traditional telecommunication networks were configured as rings since they guarantee recovery times and lead to predictable restoration paths, thereby simplifying management. Fiber usage can be low in ring solutions because of the requirement for protection fibers on each ring. A mesh physical topology is more efficient when the demand pattern is also meshed. Besides, network designs rarely resemble rings since fibers can be routed only along rights-of-way which may not facilitate a ring topology. Building rings on top of meshed fibers results in a logical overlay which is harder to design and maintain. Mesh networks allow a topology similar to fiber routing. Also, the benefits in flexibility and efficiency of mesh networks are potentially great. Protection can be based on shared paths, thereby requiring fewer fibers for the same amount of traffic and can lead to efficient wavelength utilization. However, mesh networks require a high degree of intelligence to perform the functions of protection and bandwidth management, including fiber and wavelength switching.

Broadcast-and-select topologies in LANs based on passive star couplers have star topologies, but the actual switching components in such topologies are located at the sending NICs, which makes this equivalent to a single shared-link bus topology. Some recent optical network architecture proposals are based on hierarchical star topologies in which the switching points closer to the end-user perform traffic multiplexing without any packet-by-packet processing, thereby exploiting large capacity of fibers, and feed large traffic aggregates to few large packet-switching points. The hierarchical-stars topologies of these proposals are in many ways similar to what was used in traditional telephony, and in several switched Ethernets LANs. Whether there are intrinsic advantages to challenging the hierarchical structures of Ethernet-based LANs and arbitrary-topology MANs and WANs due to optical technology constraints remains to be seen.

A.2.3 Evolving Control-Plane Issues

Network control plane will play a key role in the development of next-generation network architectures. Multiple control-plane technologies are under active development including ones based on GMPLS to support optical circuit-switched networks, and other control-plane solutions to support optical burst-switched and optical packet-switched networks. As in traditional telephony and other circuit-switched networks, optical networking also requires separation between transport and control planes. The advanced features to be incorporated into specific network architectures may include the use and management of parallelism to augment backbone capacities based on edge requirements, dynamic provisioning of network resources based on traffic conditions or user requests, and movement of data across layers of network technologies to satisfy a particular performance and/or capacity requirement. (Please see Appendix C on control-plane issues for further discussion on this topic.)

A.2.4 Emerging Application-Centric Architectures

Many applications are emerging, particularly in the large-scale science communities, which require that a set of devices around the network be connected by high-bandwidth pipes (with quickly-reconfigurable capacities as well). The embedding of such a set of bandwidth pipes is synonymous to the creation of a virtual private network (VPN), and is referred to as a **"Lambda Grid"** (or just **Grid**) in the optical networking context. This virtualization is possible because the optical network actually consists of multiple levels (which should not be confused with the layers of the "cross-layer design" mentioned elsewhere in this document). At the lowest level, we have the topology of the fiber layout. But fiber is laid in bundles (with densities approaching 1000 fiber strands per bundle), so by splicing together fiber strands in different bundles, long fiber links can be created. The collection of such fiber links forms the physical fiber-link topology, which is embedded on the fiber-bundle topology. Noting that each fiber strand can support many wavelengths (160 today, and expected to grow to 320 soon), an additional level of virtualization can be performed, by considering wavelength-paths, called lightpaths, on the fiber-link topology, as was the case with the Grid example above. Working recursively, and noting that the capacity of a wavelength can also be sliced up in the time domain, one can create powerful multi-level network architectures to suit the appropriate sets of networking applications and their needs. The corresponding research problems in multi-level networks, in general, and Grids, in particular, are aggressively emerging and need to be identified and attacked. Please see Section A.5.1 for an example of such an architecture.

A single network architecture which could respond to a variety of service requirements would be a lofty research goal. In this context, a set of network services should be identified to inform and drive the resulting network architectures. Some service requirements will require extremely fast provisioning of low-latency, high-bandwidth end-to-end paths. Other service requirements may include the ability to dynamically adjust capacity between routers to aggregate small flows in a manner invisible to the end users. A possible way to realize this is through a "Service-Driven Network Architecture" where the requirements of the transported data are used to determine the most appropriate architecture.

A.2.5 Integration of Optical and Wireless

Since wireless technology is evolving very fast, innovative use of optics, be it free-space or fiber-optic, to extend the reach of (RF) wireless communications, to eliminate interference and facilitate interoperability in wireless networks (by providing transparent pipes), and reduce the cost by converging fixed and mobile infrastructures into one (e.g., WiMAX-based cellular access with optical backhaul) is worth investigating. A typical example is described in more detail in Section A.5.2 for multimedia services on a train.

A.2.6 Dependability Requirements

Optical networks are the ultimate solution for robust networking in general: fiber is the best tunnel to secure the current Internet traffic. Future networks will undoubtedly deploy optical network technologies to increase robustness and the question arises: how to design optical networks to elegantly recover from such failures because of the huge amount of data loss it can potentially suffer. Important objectives for these recovery mechanisms are low recovery time and large scope of failure scenarios (to avoid major impact on running services), scalability and stability, signaling requirements and state overhead, capacity requirements, etc. The correlation between survivable network architectures and network security should also be studied. The interplay between overload, faults, and attacks needs investigation as well.

A.3 Motivation for Architectural Change

Based on the above discussions in emerging trends, radically new architecture concepts are needed. For example, to efficiently combine innovations in wireless and optical technology applications in a fast-moving environment requires a network architecture that supports mobility, handover, traffic grooming, and traffic management under a control plane that efficiently makes use of resources while improving the overall quality of service to users. The main motivational factors are the following:

- Application-specific adaptable architectures.
- Access speed of tens of Mbps to Gbps and scalable to higher rates.
- Access network design will justify the core network design.
- Variable number of users, small to large, each offering variable number of jobs.
- Finding resources for users with certain guarantees such as fast reconfigurability.
- Unicasting and multicasting applications.
- High bandwidth needs and mobility.
- Dynamic architecture that envisions how the environment will change.
- Need for universal services such as telephone jacks and electricity/power points, e.g., Ethernet jack and wireless access points.
- Need for plug-and-play device. Are today's wireless and Ethernet sufficient as plug-and-play devices?
- Anticipated kinds of services needed in the future:
    - For example, are the services described in Section A.5 sufficient or will they be very different?
    - E-science applications which initiate end-to-end optical connections by issuing signaling requests.
    - Different services for storage-area network.
    - Remote surgery needs different adaptability and quality of service.
    - Scientists use connection to send data across the network and use resources.
- Security challenges.
- Accounting and billing challenges.
- Protocols developed 20 years ago have been extended to accommodate various changes in technology and compatibility that makes them outdated and convoluted. So a new architecture will require development of new protocols that are clean and concise.
- How are new architectures constrained by existing networks and technologies? For example, do considerations for the IP embedded base hold back optical researchers? Customers care about IP, while operators care about operating their optical networks efficiently. The new architectures must satisfy both needs.
- Some other issues are related to how the new architecture will deal with the existing world and technologies. For example, does considering IP hold back optical researchers? Customers care about IP, operators care for optical network. The new architectures may satisfy both paradigms.
- New architectures may allow merging of current networking layers, e.g., layers 2 and 3.

Using many of the above arguments, one needs to design cutting-edge architectures that are suitable for Years 2010, 2015, 2020, and identify what they will do for society.

The availability of optical transmission and switching may change network design criteria. Packet networks were introduced basically to optimize bandwidth usage at the cost of extra information processing in switching nodes. However, in the optical domain, bandwidth on fibers is abundant, and processing capabilities are limited. Network optimization criteria are therefore expected to change, with significant effects on architectural design. An important design criterion could be the minimization of network-wide packet-by-packet processing.

A.4 Design of New Network Architectures

Conventional architectures use Optical Circuit Switching, Optical Packet Switching, and Optical Burst Switching. Considering the emerging trends and technologies, the issues that need to be addressed for future networks are described below.

A.4.1 Design of Architectural Concepts

Identification of architectural concepts that meet and respond to most of the motivational factors is an important and first issue in the design of a new architecture.

A.4.2 Holistic Design

Optical networking, just like wireless networking, is a highly interdisciplinary research area. It requires sound knowledge on a very diverse set of disciplines: from communications to optics to electronics to computer architecture to algorithms to network protocols to operations research to telecom business models. Traditionally, in optical networking, most of the emphasis has been put in the (bottom-most) optical layer. However, history has taught us that, without sound architectures, applications, and economic models in mind, one can produce technologies with limited or no usefulness. Thus, the future optical network should not be designed bottom up; neither should it be a top-down design in which case the applications and network architecture layers operate in isolation from the physical layer. Instead, the network should be based on a "push-pull" design where all three layers (physical, network, and application) work together harmoniously. Such holistic (or cross-layer design) problems should be encouraged.

A.4.3 Reconfigurability Issues

The issues surrounding the agility and reconfigurability of optical networks have been a field of intensive research in the past. Most of the work seems to have focused on Routing and Wavelength Assignment (RWA) and grooming in fully-reconfigurable networks. Yet, there is no clear consensus on the degree of agility and reconfigurability required in optical networks. Approaches to quantify this must be developed. Methods to quantify the performance of networks with Reconfigurable Optical Add-Drop Multiplexers (ROADMs) must be developed and trade-offs between transport capacity, network reconfigurability, and agility of end nodes must be studied. In the case of packet-switching end nodes, while the aggregate bandwidth is limited by the need of interfacing with the (electronic) application domain, the availability of WDM and of a moderate degree of wavelength agility would enable interesting possibilities in terms of dynamism in resource allocation, and fault recovery and resilience.

A related issue is the development of suitable performance measures and traffic models. Traditional models such as Poisson traffic and blocking probability are not appropriate for large-scale optical networking and new models and measures need to be investigated.

A.4.4 Cross-Layer Issues

Traditionally, optical networks have been designed and architected using a strict hierarchical layering, but transparency calls for new approaches that jointly optimize the functions of different layers. Consider the following example.

The admission of a lightpath not only involves RWA, but also an evaluation of the quality of transmission through such measures as bit-error rate (BER) or Q-factor at the receiver. Furthermore, setting up a lightpath may impact other lightpaths that are already active, thus leading to a complex interaction among the various lightpaths in the network. Handling this situation requires jointly considering the physical layer and the network layer.

Thus, new approaches for power, routing, and wavelength assignment (PRWA) that consider the quality of transmission as well as the impact of other lightpaths are needed. The availability of optical 3R regeneration (reamplification, reshaping, and retiming) is obviously a key point here. 3R would decouple the design of transmission links from network design. The feasibility and cost viability of 3R therefore deserves further investigation.

A.4.5 Higher-Layer Protocols

Past research has primarily focused on routing and lower-layer protocols, and little attention has been paid to the transport layer and application protocols for optical networks. Efficient transport-layer protocols for dynamically-switched optical networks, based on circuit or burst switching, as well as application protocols for optical grids, will become more important as optical technologies mature.

For instance, the potential of burst switching, in general, has yet to be fully explored. For the most part, research on OBS has focused on very specific OBS architectures and on several fundamental issues, such as signaling protocols, burst assembly, and contention resolution. Continued research in these areas is likely to be somewhat incremental; therefore, for OBS research to have a greater impact, OBS must be viewed within a wider context, as follows.

- One potential avenue of research is to investigate OBS in the context of specific applications, such as Grid computing, storage-area networks, or other applications that require bulk transfer of information. In such specialized settings, it is possible that OBS can be tailored such that it is the best possible solution for meeting the requirements of the specific applications.
- Another area of OBS research that would be useful is the integration of OBS with existing protocols, such as TCP/IP.

Such research would provide solutions for optimizing OBS for existing networks. The research focus need not be confined to traditional OBS architectures alone. In particular, if issues such as lack of buffers cannot be resolved satisfactorily, then alternative burst switching architectures must be considered. Examples of such approaches include the use of light-trail architectures to support bursts and the use of electronic buffers and components to support burst switching. In the latter case, the burst-switched network would retain some of the benefits of all-optical OBS without being subject to all of its constraints. The application of burst-switching concepts to other areas of communications, such as wireless and satellite communications may also be of potential interest.

A.4.6 Control-Plane Issues

The GMPLS control plane can provide rate-guaranteed switched virtual circuit (SVC) services. Service providers currently see no business plan to offer SVC services. Specific needs in design of control-plane protocols must be addressed and are identified in a separate section. Control plane solutions should address issues in hybrid wireless-optical networks, applications such as watching TV-on-demand, connectivity on trains and planes, support for classes of application that make use of the global infrastructure, support service-layer adaptation of applications, support powerful recovery mechanisms and should be able to customize the service-plane layer via programmable features. Such control planes will require more interaction between the various layers and researchers need an understanding of multiple layers.

A.4.7 Tools and Methodologies for Studies

Since optical networking is new, there is a lack of understanding as to how to compare different optical networking architectures and protocols. More specifically, there are questions as to what the traffic characteristics are, which in turn depends on the existing and foreseeable applications to be run on optical networks. For instance, which is more representative of the traffic patterns in optical networks -- smooth, constant bit-rate type, or a bursty self-similar type? Also what are the appropriate performance metrics to be used, e.g., is request blocking probability in a circuit-switched network a fair measure when comparing different protocols or should new metrics based on revenue/profit be developed? Finally, how can different switching paradigms such as circuit switching and burst switching be compared under common assumptions and using common performance metrics?

A.4.8 Architecture-Level Simulator

There is a need for a large-scale, comprehensive simulator for optical networks. Simulators developed by researchers are mostly ad hoc and cannot be easily modified if the assumptions are changed. Commercial simulators focus on optical transmission for the most part and are too detailed and slow for network simulation, whereas network simulators generally ignore physical-layer effects. A concerted large-scale effort by the research community is needed to develop an open-source, modular simulator. The simulator must be able to work at several levels such as: packet, burst, flow, and circuit. It must provide for the monitoring of several different performance measures such as packet delay and blocking probability, and must consider multiple layers such as physical, wavelength, network, etc.

A.4.9 Testbeds

The conceptual studies and solutions should also be backed by extensive experiments on a real-life testbed. Crucial issues are assessment of performance, interoperability tests, coordination between equipment from different sources (vendors), etc.

A.5 Examples of Application-Centric Network Architectures

A.5.1 Consumer Grid Example

Consider a multimedia editing application, where integrated audio and video manipulation programs are widely adopted, allowing users to manipulate video clips, add effects, restore films, etc. Advances in recording, visualization, and effects technologies will demand more computational and storage capacity, especially if the editing is to be performed within a reasonable time frame (allowing user feedback). More specifically, 1080p High Definition Television (HDTV) offers a resolution of up to 1920x1080 pixels, amounting to around 2 MPixel per frame. Suppose that applying an effect requires 10 floating point operations (Flop) per pixel per frame, and the user would like to evaluate the effect for 10 different options; then processing a 10-second clip (at 25 frames per second (fps)) will require over 50 GFlops of computation. This will take about 5 s to complete locally, assuming local processing power is 10 GFlops. However, if service providers offer resources having a 100-fold capacity, execution time should only take 50 ms. Transmission time of 10 s of compressed HDTV video (bitrate 20 Mbps or a 25 MB filesize) is reduced on a 10 Gbps access link to 20 ms. A Grid user simply creates an optical burst containing the multimedia material to be processed, and hands over this burst to the network. The network is then responsible for delivering this burst to a resource with sufficient capacity. As such, important improvements in application response times can be achieved, making interactivity possible for applications that are otherwise too resource intensive. Also observe the rather modest requirements of the Grid job for both the computational resource and the network resources, although a large number of such jobs will be generated at unpredictable times and locations in the network.

A.5.1.1 Basic Technological Solution

An essential requirement to deliver Grid computing capabilities to consumers is a sufficiently powerful access network (see Figure 1). Current Fiber-To-The-Home (FTTH) initiatives utilizing Passive Optical Network (PON) technology can already deliver 100 Mbps speeds to end users. The apparent unlimited capacity of fiber, however, makes access speeds of 1, 2.5, 10 Gbps and higher possible within a timeframe of 10-15 years. Obviously, the capacity of the edge and core networks will need to be scaled in parallel to keep up with traffic generated by end users.

Traditionally, transferring data over optical networks takes place over a lightpath, which is a complete wavelength channel reserved for exclusive use between two endpoints. Significant amounts of bandwidth would be wasted with this technique, considering the limited data sizes in a consumer scenario. Optical Burst Switching (OBS) is a technique that allows reservation of bandwidth smaller than a full wavelength. Since each job is individually packaged in a burst, these can be treated (routing, scheduling, and resource reservation) independently of other bursts in the network. This flexibility allows the Grid network to adapt quickly to changes in generated load and resource availability.

Users will be able to gain access to the actual Grid resources such as computational, storage, and information resources at several locations. First, a large number of end users' desktop PCs are mostly idle and can be made accessible for remote processing. Second, opportunities will emerge for Grid Service Providers that can offer powerful and dedicated resources to users. These resources can be optimized for a specific functionality (e.g., video transcoding) or offer generic processing or storage capabilities.

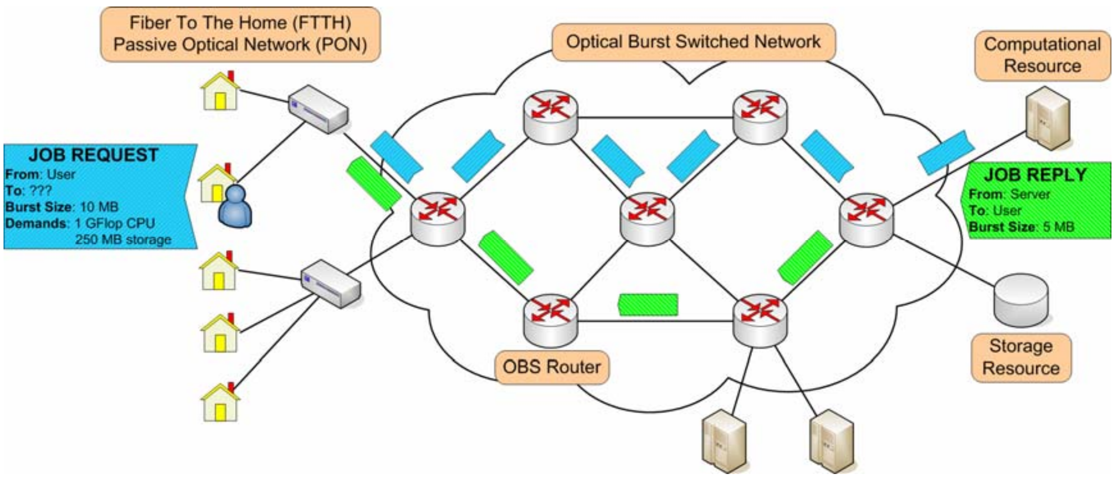

Figure 1: Overview of OBS-based consumer grid.

A.5.1.2 Basic Technological Challenges

Although a large number of dynamic users must be supported, each individual has fairly modest resource requirements. Specifically, given the limited data size of a job (on the order of 1-50 MB), the job will need bandwidth of sub-wavelength granularity. Optical Burst Switching (OBS) has been proposed as an enabling technology and it allows flexible and adaptable routing for unpredictable network traffic.

The successful realisation of consumer Grids is highly dependent on the widespread use of photonic technology throughout the network. It is essential for users to gain access to remote resources through a high-bandwidth, low-latency network. For instance, transferring 10 MB of data over a 1-Gbps link takes only 40 ms, leaving sufficient time for processing and returning results, ultimately creating a (near) real-time user experience.

It is however important to have optical routers capable of analysing job information at very high rates. For instance, a 10-Gbps link can carry 1250 bursts of 1 MB, indicating the analysis and scheduling of each burst can only take 0.8 ms. This problem becomes even more important when higher line rates are considered.

A.5.1.3 General Research Challenges

The above consumer Grid scenario illustrates the main challenges and opportunities for realising distributed computing capabilities on a consumer level. Optical technology will be indispensable to provide high-bandwidth, low-latency connections. The large number of dynamic users demanding large resource capacities and support for Quality of Service (QoS) indicates that a highly scalable infrastructure is needed. In particular, resource management and job scheduling must be fully distributed and tightly integrated in the photonic control plane. Finally, the use of OBS as a photonic switching technology can offer the required fine-grained access to bandwidth while retaining a flexible and scalable job-delivery method.

A.5.2 A Mobile Multimedia Services Example: Internet-on-the-Train Scenario

To provide the current spectrum of multimedia services (e.g., Video-on-Demand, online gaming, etc.) to train passengers, train carriages need huge bandwidth. We can assume that the broadband connections in a train will follow the connections available at home (nowadays on the order of 5 Mbps) with a delay of some years (say five years). To assess the total bandwidth needed on the train, we have to estimate the number of users. For example, a Thalys train is equipped with 377 or 754 seats (and recent ones have about 1500 seats). During rush hour, the seating capacity of the train will be nearly completely occupied, and supposing 20% of the passengers want to have broadband access, we need a total bandwidth of nearly 400 or 800 Mbps on the Thalys trains (and 1.5 Gbps on the new train). In the future, bandwidth of 100-1000 Mbps will be available at home. To offer this to train passengers, a total bandwidth of 100 Gbps will be desired.

A.5.2.1 Basic Technological Solutions

<u>(a) In train network:</u> In the train carriages, the Internet connection can be provided by the same technology as in homes, e.g., WLAN 802.11 technology (or its successors). With the help of one (or more) access point per carriage, all passengers can have Internet access.

<u>(b) Network between train and fixed network:</u> Next to the distribution in one carriage or between carriages, a more challenging problem is the connection between the fixed network and the train itself. Nowadays, the most used technologies are satellite and cellular solutions (e.g., GSM, GPRS, UMTS). Since satellite connections have a considerable inherent delay (approx. 500- 600 ms) and they are limited in bandwidth (which becomes an important consideration when a large number of trains is using internet access), they are not suitable for broadband access in trains. As a consequence, they cannot be considered as a long-term solution. Present cellular technologies provide much lower delays, but they have a much lower date rate than the desired figures.

One important solution to bring high-speed Internet connections to the train is to use the cellular principle but adapt it to much higher speeds (e.g., by using WLAN standards in a cellular mode). The reduction of the cell size (e.g., 100-m cell diameter) and the adaptation to a one-dimensional cell pattern are two important aspects to succeed in the challenge described above. With a cell diameter of 100 m, the cell size is shorter than the train length, and instead of one antenna for the whole train, it is also possible to place, for example, one antenna per carriage. An increasing handover rate is an important consequence of reducing the cell size. A high-speed train running at 300 kmph in combination with a cell size of 100 m corresponds to one handover every 1.2 s.

With current handover times on the order of 0.1 to 1 s, this is intolerable. Thus, it will be very important to minimize the handover times.

<u>(c) Fixed network:</u> An additional challenge will be the development of a fixed aggregation network interconnecting all these cells along the railway tracks. When a train is moving at a speed of 300 kmph, the traffic in the aggregation network has to follow this train (e.g., a train going from Brussels to Paris will result in a 1 Gbps connection that starts in Brussels and has been rerouted continuously till the train arrives in Paris after about 1 hour).

A.5.2.2 Basic Technological Challenges

Several antennas along the railway can be grouped (e.g., over a distance of 5 km) and then supervised by a central control station (in a gateway) that feeds all these antennas via an optical network (see Figure 2). The combination of this optical feeder network with the (further described) moveable cell concept offers a possible solution to minimize the handover times. An aggregation network has to feed the gateways to the grouped antennas. With an example distance of 5 km between these gateways, connections of several Gbps, feeding the whole train, have to be set up and broken down every minute. This leads to extra requirements and challenges for the aggregation network (which could be based on dynamic optical circuit switching or OBS).

To solve the handover problem, instead of having the train moving along a fixed cell pattern, one might also consider reconfiguring the optical feeder network in order to have a cell pattern moving together with the train (see Figure 3, where the radio frequencies are moving from one fixed antenna to another at the same speed as the train). In this case, the latter can communicate on the same frequency during the whole connection and also avoid (most of) the cumbersome handovers. It is clear that synchronizing the speed of the cells with that of the train is of utmost importance and that the required reconfigurations should be kept as short as possible. This concept of "moveable cells" is very attractive in a train scenario, because the advantage is that all users move at the same speed. It is possible to implement this moveable cell concept with a few optical switches (e.g., a semiconductor optical amplifier (SOA) used as switch, a micro electro-mechanical system (MEMS) switch, etc.) so that the reconfigurations take place entirely in the optical domain. The switchover of only one or two optical switches in a central station will be much less time-consuming than the classical handovers. Optical switching times on the order of ns or μs are already possible, and when these switching times correspond to the dominant factor in the handover time, the latter will reduce by many orders of magnitude.

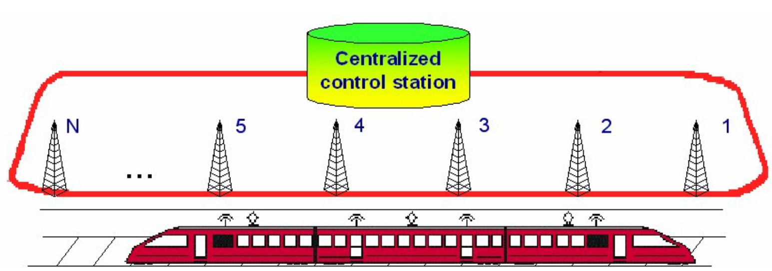

Figure 2: Antennas along the railway grouped and controlled by a central control station (at the gateway to the aggregation network).

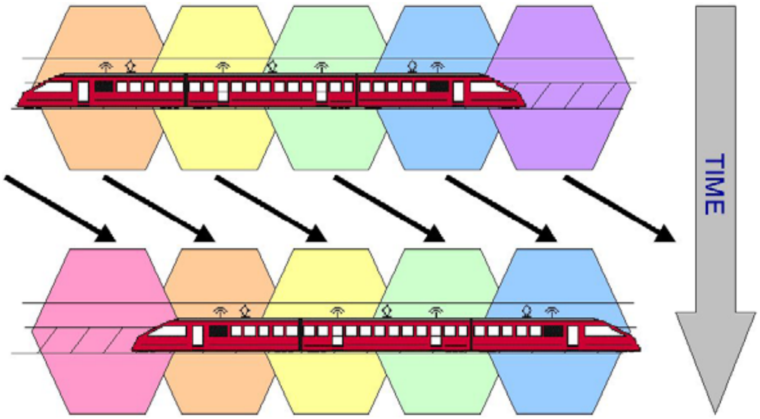

Figure 3: Illustration of the moveable cell concept.

A.5.3.3 General Research Challenges

The above train scenario illustrates the challenges and opportunities for realising broadband access in fast moving vehicles (cars, trains, etc.). To provide huge bandwidth, optical technology will be indispensable. In the access network, flexibility will be key to avoid large handovers, imposing fast optical switching times. In the aggregation network, it is important to investigate which techniques (e.g., variants of OBS or automatically-switched optical network (ASON)) would be suited to reconfigure the network regularly, while minimizing the bandwidth usage and operational cost.

Appendix B:

Research Issues in Optical Hardware Components and Systems

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B.1 Optical Hardware Systems

The hardware system starts where the information is generated, processed, and stored; and it ends where remote users can access, retrieve, and receive the information through optical transmission and switching systems.

Optical hardware system technologies, consist of six categories in terms of communication distances, as follows.

1. Optics to the chips for communications within a few centimeters. It includes silicon photonics and photonic integrated circuits (PICs).
2. Board-to-board and backplane optical interconnects for communications from a few tens of centimeters to a few meters. It includes optical interconnects to processor and memory systems and backplanes with data rates of 2.5 Gbps, 10Gbps, 40 Gbps, and beyond.
3. Home, automobile, and avionics optical networking, for communication distances of a few meters to tens of meters. It includes new optical transmission medium such as polymer waveguides, POF, MMF, and ROF for convergence of broadband wireless and optical wire communications.
4. Broadband access networks from 100s of meters to a few tens of kilometers. It includes fiber-to-the-home (FTTH), gigabit Ethernet, hybrid-fiber-coax (HFC), Optical code-division multiple access (CDMA), and wireless-over-fiber technologies.
5. Metro networks spanning distances from tens of kilometers to a few hundred kilometers. It includes reconfigurable add-drop multiplexer (ROADM) and optical crossconnect (OXC) for GMPLS-based circuit-switched networks and optical label and packet routers for packet-switched networks.
6. Long-haul networks covering hundreds to thousands of kilometers. It includes highly spectral efficient, and robust modulation format technologies.

B.1 Research Topics in Hardware Systems: General Considerations

Optical networking hardware supports and performs system functions in metro and long-haul transport architectures. It also supports connectionless and connection-oriented packet-switched architectures and dynamic circuit-switched architectures. The general issues for developing hardware systems for telecommunications are the following:

- *Cost and Function*: Any new network hardware needs to achieve a cost objective. Otherwise the system will not be able to be deployed competitively. The transmission links are always implemented in optical domain. However, the switching, crossconnecting, multiplexing, and regeneration functions can be implemented in either the optical or electronic domain.

- *Speed:* The line speed is defined as optical transmission bit rate for accessing, regeneration, amplification, switching, multiplexing, and add/drop multiplexing in the optical domain. Thus it will allow optical signals passing through multiple optical links/nodes.
- *Channel capacity:* It is closely related to the spectral efficiency of WDM systems and throughput of the network. To realize the advantages of high channel capacity of optical networks, significant research activities are required to enhance optical technology, particularly in wavelength channel spacing and high-speed robust modulation formats.
- *Size and Density:* Making hardware components and systems smaller will allow efficient use of limited central office space by increasing the density of integration.
- *Power Dissipation:* There is a finite power budget from the chips and modules to all the way to systems, so we need to lower the power dissipation per gigabits of information transmitted or switched.
- *Modulation Formats:* It is the system capability for transmitting and switching data streams independent of bit rates, modulation formats, protocols, etc.
- *Wavelength Conversion:* How often do we need it? Where are they placed? Should they be optical-electrical-optical (OEO) or all-optical (OOO)? What are the cost and conversion efficiency?

Given the above classification of six categories of hardware systems to cover various distances for optical interconnections and communications networks, all generic issues described above are applicable here. Implementation of these general requirements in optical domain requires further advances in optical technologies.

B.2 Current Issues and Trends

B.2.1 Transparency

Multichannel optical amplification by erbium-doped fiber amplifier (EDFA) developed in late 90s set the pace of that decade's transparency research for optical networks. One of the famous talks at OFC 2000 by Adel Saleh started the "island-of-transparency" concept for metro networking. The key issues are how do we grow the "islands" in size and how high is the bit rate we can transmit and still maintain the transparency of bit rates, formats, and protocols. So far we all agree that the strength of optical networking is not to process the data bit-by-bit in the network. Transparency at 2.5 Gbps rate can be achieved today while transmissions at 10 Gbps and 40 Gbps are still undergoing research. It is achievable in a fixed path but it is far more difficult to change paths dynamically. The main obstacles are network impairments such as different signal power levels, chromatic dispersion, PMD, etc. It is a challenge to generate a dynamic transmission compensation map when optical switching and multiplexing are required.

B.2.2 Dynamic Reconfiguration

In general ROADM and OXC are mature technologies and optical MEMS switch are main device driving force to make them available in commercial products. Network operators have been focusing on creating a new reconfigurable network based on MPLS and GMPLS concepts. But full deployment is still years away.

B.2.3 Performance Monitoring

For perfect network monitoring, bit-error rate (BER) detection at every node would be ideal but it is extremely difficult to implement due to cost and technical complexity. Here comes the next question: "is Q monitoring sufficient?" The optical signal-to-noise ratio (OSNR) derived from Q measurement is sufficient when there are no other nonlinear or signal crosstalk issues in the network.

B.2.4 Optical Interconnect

The goal of optoelectronic integration is to provide high bit-rate density solutions at low cost as the bit rate per channel approaches 10 Gbps and beyond and the copper option become less tenable. Of course this is also the goal of the high-performance computer industry at large which propels worldwide research and development on optoelectronic solutions.

The most common industry-wide approach is embodied by the optoelectronic circuit board (OECB) which is being developed worldwide in order to transcend the performance limits of copper interconnects in blade servers and supercomputers. The state of the art for optical-digital integration is to bond active optical components -- lasers, laser drivers, photodetectors and associated amplifiers -- to a peripheral ball grid array (PBGA) package that may eventually also contain a memory controller with multiplexer/demultiplexer. The entire package is then flip-chip bonded to the transceiver portion of a circuit board. In this approach, optical coupling from an array of vertical-cavity surface-emitting laser (VCSEL) sources to the lightwave circuit is accomplished by microlens relays and waveguides with 45^{o} end mirrors. A similar optical coupling arrangement is used for the photodetector array. The active optical alignment is largely a manual operation of pick-and-place tools, and displacement tolerances have to conform to prevailing pick-and-place flip-chip assembly tolerances with deviations as large as +/- 10 µm. This approach has notable drawbacks:

- 45^{o} waveguide end mirrors are difficult to fabricate lithographically and suffer from sizeable insertion loss unless metallized. Even with metallized end mirrors, insertion loss due to mode redistribution is always present.
- Lenslet relays can be fabricated fairly easily but the relative alignment and insertion loss is also subject to fairly large assembly tolerances and board warping.
- A potentially major drawback is the use of a PBGA which severely limits scalability. The PBGA takes up valuable board space, can only be placed a few centimeters away from the nearest processor and limits the number of I/Os; therefore "optics to the processor" becomes limited to "optics near the processor."

B.2.5 Access Bandwidth

Recent advances in optical components and technologies enable new and advanced network access at high bandwidth. These new technologies include the large increase in bandwidth enabled by WDM systems, the ability to provide WDM light sources in central offices or optical line terminal (OLT) through WDM multiplexter and demutiplexer in passive optical networks (PONs). In general, symmetric upstream bandwidth can be provided by modulating a wavelength channel provided by OLT through PONs. In this way, the cost can be contained since we can avoid a difficult wavelength monitoring task at the customer premises. Japan is pushing for FTTH with 100 Mbps to customers. Korea is the only country that has a program to develop WDM-PON for commercial deployment. The biggest obstacle is that there is no WDM-PON standard so far. There are many issues to be resolved such as channel density, ultimate bit rates, system margin, and distance covered. These access technologies will not only enable new and advanced network services, such as symmetric data access, IPTV, and interactive games but they will demand new core and metro infrastructures to support inexpensive 2.5 and 10 Gbps client network interface cards (NICs) at the edge of the network. This will require an end-to-end network architecture which can provide for innovative and dynamic use of the optical network resources and transport systems to provide intelligent management of user data flows.

B.2.6 Protection and Restoration in Optical Networks

Conventional proactive protection or dynamic restoration schemes are commonly known to restore end-to-end path services in the event of network failure. In both schemes, once the primary path fails, all the information in transmission at the time of failure is lost unless the backup path is activated. Furthermore, the network has to wait for the duration of the restoration time to be back in operation. This will incur extra bandwidth consumption and jeopardize time-critical data services.

The challenges of reliable data delivery with system innovations include: managed transparent reach with low BER floors, transparency to diverse line rates and formats, improved overhead bandwidth efficiency, instant data recovery by eliminating restoration time, and simplified network control. The primary techniques to construct these solutions are: robust optical signal transport, efficient information coding, and novel network control algorithms. The data are encoded and decoded at the source and destination, and can be carried by multiple wavelengths or multiple data channels in a fiber over multiple disjoint lightpaths.

B.2.7 Ethernet over Metro

One of the primary concern of optical networking technologies is that the existing telecommunications network was built to handle voice traffic through circuit-switched networks. However, with ever-increasing packet traffic generated in Ethernet-based local-area networks, we need to resolve the traffic conversion and multiplexing at the network edge. There are three potential solutions being investigated: (1) change the core network to an optical packet-switched network, (2) use data mapping methods such as Generic Frame Protocol (GFP) to carry Ethernet frames over SONET/SDH for data transmission in the metro networks, and (3) use native Ethernet format over an optical network directly. The first method is still in research stage and will be covered by an OPS/OLS section later. The second method is the prevailing solution in the industry which relies on the design and manufacturing of new silicon chipsets. The third solution is related to network transparency issue. It is relatively easy to run Gigabit Ethernet over metro optical network at 1Gbps but more difficult for 10Gbps Ethernet. A single packet-switched optical network architecture which could meet a variety of service requirements is still a challenging research goal.

B.2.8 Convergence of Optical and Wireless Access

Since wireless technology is evolving very fast, innovative use of optics, such as free-space or radio-over-fiber technologies have been explored to provide ultra broadband wireless channels at 1 Gbps and beyond per channel. Combining optical access networks of the future such as WDM-PONs can extend the reach of broadband wireless communications, and eliminate interference and facilitate interoperability in wireless networks (by providing transparent pipes), and reduce the cost by converging fixed and mobile infrastructures into one. In serving hot spots of wireless (WiFi or cell) access areas such as airports, multiple antennas connected by an optical fiber access network could be an attractive solution to respond to the mass-communication needs in a timely manner. The advantages are reliability and high bandwidth.

B.2.9 Local Access and Home Networking

Low-cost, broadband access to the home or small-business user is still a challenge. The state-of-the-art Cable Modem in Hybrid-Fiber-Coax systems and xDSL-based Internet data access can only provide bandwidths from a few Mbps to a few tens of Mbps while optical access networks can operate at 100 Mbps to 10 Gbps. Fiber to the desktops are still the future-proof solutions for broadband access technologies but the deployment cost is a significant issue.

One possible economic solution to the last-mile access problem is to extend fiber to the home (FTTH), or at least to the curb (FTTC). Such solutions have many attractive features including seamless integration with fiber-based metro and long-haul networks. We also need to recognize the role that Ethernet-based optical access networks play. There need to be a clear solution that will provide an evolution path for access that will be upgradable and scalable as more and more users are directly connected to the backbone using high-speed optical access.

Based on the discussions in current issues and trends, radically new hardware research projects are needed. For example, to efficiently combine innovations in wireless and optical technologies to be used in a fast-moving environment requires a network architecture that supports mobility, handover, traffic grooming, and traffic management under a control plane that efficiently makes use of resources while improving the overall quality of service to users.

Using many of the above arguments, one needs to design cutting-edge architectures that are suitable for Year 2010, 2015, and 2020, and identify what they will do for the common person.

B.3 Challenges and Future Directions in Hardware Component and Systems Research

In spite of great advancements in optical components and systems in the last decade, there are still a lot of frontier left to be explored for next-generation hardware systems, e.g., convergence of optical circuit- and packet-switching systems, integration of super-broadband optical and wireless access networks, home networking, components for optical packet-switching and optical label-switching technologies. The burning issues in hardware research are listed below:

- **Devices**
    - **Silicon photonics**
    - **High temperature operation**
    - **Performance**
    - **Tunability**
- **Components**
    - **Packaging**
    - **Optoelectronic integration**
- **Systems**
    - **System integration**
    - **System interface**
    - **Network element architecture**
- **Performance monitoring**
- **Impairment remedies and compensations**
    - **Electronics vs. optics**

B.3.1 Optical Interconnects

The goal of optical interconnect research is to provide high bit-rate density solutions at low cost as the bit rate per channel approaches 10 Gbps and beyond for board-to-board and chip-to-chip optical interconnects. The concepts of bringing "optics to the processor" is being developed by a number of research institutes. The board contains an embedded, passive lightwave circuit which carries optical signals to and from a transceiver package that is not a processor. Because of the common choice of VCSELs and top- or bottom-viewing PDs, a 90^o, out-of-plane beam turn is required and is generally accomplished by using 45^o waveguide end-mirrors and collimating lenses. Generally, peripheral BGA have insufficient I/Os to accommodate processor packaging, a major restriction for this EOCB design. The electrical output of the receiver package has to be a-transmitter to the processor a few centimeters away.

There are only two key technology barriers to achieving high performance optics to the processor and high-performance board-to-board optical interconnects: (1) cost per bit and (2) reliability. Bit density is not an issue because waveguides can achieve a 10 μm pitch over meters without crosstalk and the bandwidth per channel can be 40 Gbps. The cost per bit is determined overwhelmingly by assembly cost. Reliability is determined primarily by laser FIT (number of failures per billion hours of service) and the behavior of the polymer channel in the field. The latter is the only open question.

To solve the cost problem per bit, we can explore a parallel optoelectronic integration process. This means that, in the most critical step, the alignment of laser and detector to the lightwave circuit, one channel or 100 channels are aligned in the same amount of time, usually one minute.

The problem of cost per bit can be further resolved by using directly-modulated edge-emitting lasers at 10 GHz. VCSELs roll off rapidly after 3.3 GHz and emit less power. We need to engage VCSEL research at high bit rates (≥ 10 Gbps) and longer wavelengths (1310 nm and 1550nm).

B.3.2 Home Networking

We need to identify important devices and systems that meet and respond to most of the requirements in the design of a new home networking architecture, as follows.

- Low-cost and low-power devices and components
- High-speed and high-efficiency light-emitting devices
- Millimeter-wave photonic components
- Packaging and motherboard technologies
- Remote optical powering
- Interface to residential getaway
- Radio-over-fiber and ultra-wide-band techniques
- Low-cost integrated base stations.

B.3.3 Centralized Light Source for WDM Access

New schemes to control and generate WDM lightwave sources in both time and frequency domains are needed. Optical communication traffic for Internet services is expected to double every 9 months; the volume to petabit/sec throughput; and the access bandwidth for each user at 100 Mb/s to 2.5 gigabit/sec in the near future. All these requirements are leading to the explosion of research activities in cost-effective versatile laser technologies for high speed, reliable and scalable networks. To unlock the available fiber capacity and to increase the performances of optical networks, wavelength division multiplexing (WDM) techniques, multiwavelength and picosecond pulsewidth laser technologies have been significantly advanced because of many advantages: simple structure, low cost and agile. Instead of using many different laser diodes; one simple and agile laser in our design could replace them all. It implies more functions, less cost, less maintenance and less inventory. It attracts many potential applications, such as WDM passive optical access networks for symmetric traffic, optical fiber sensors, optical instrument sensing, spectroscopy, implementation of Optical Code Division Multiple Access networks and also time-to-wavelength- division multiplexing.

Two categories of multi-wavelength laser research are of strong interest here: continuous-wave and pulsed sources. For pulsed sources, we need to concentrate on the generation of simultaneous and alternate pulse trains in the same structure. In the first case, all the different wavelengths are contained in each pulse, whereas in the other case, successive pulses are emitted at different wavelengths. To practically implement such lasers, the control of gain medium and agile filtering in the cavity are the prime focus. To produce ultrashort pulse trains at high repetition rates, active modelocking is achieved by direct modulation of the optical field during each laser cavity round trip via an active component.

There is a need to investigate how to reduce the spacing between the different emitted wavelengths while maintaining a stable laser output to avoid pulse dropout. It would be desirable to create a new, versatile multi-wavelength laser source to serve as a centralized light source in a WDM-PON. To optimize the transmission distance and the data rate, one has to investigate the chirp of the produced pulses and how to reduce the chirp to produce Fourier Transfer limited short pulses.

B.3.4 Protection and Restoration for Future Networks

Some new networking applications require robust data delivery in the optical core and resilient data coding at the edge, where high-performance memories and processors are readily available. This will create a merger of optical communication, information coding, and signal computing capabilities as never before. All these requirements are leading to the urgency of research and development of new optical networking technologies for delivering time-critical voice, data and multi-media services in a tightly integrated high-performance communication and computing network.

A fundamental challenge for realizing these systems is to deliver time-critical services while simultaneously maintaining integrity and survivability of data in case of network failures. The challenges in research and development include both theoretical and experimental approaches to design and build a resilient and survivable optical network for data delivery. One key approach is to develop novel unequal and multi-channel signal-processing techniques for optical data encoding and decoding at the edge and exploit packets over multi-channel transport in the core to ensure reliable services. Thus, the network has the ability to recover from failures and the requirement of maintaining continuity of data services at the presence of undesirable interruption including human errors and natural disasters.

The challenges of reliable data delivery require system innovations that include: managed transparent reach with low BER floors, transparency to diverse line rates and formats, improved overhead bandwidth efficiency, instant data recovery by eliminating restoration time, and simplified network control. The primary techniques to construct these solutions are: robust optical signal transport, efficient information coding, and novel network-control algorithms. We would like to deliver data that are encoded and decoded at the source and destination and are carried by multiple wavelengths or multiple data channels in a fiber over multiple disjoint lightpaths. To set up a lightpath may impact other lightpaths that are already active, thus leading to a complex interaction among the various lightpaths in the network. To efficiently deal with this situation requires a joint consideration of the physical layer and the network layer. We need a low-cost and effective performance monitoring method described before.

One of the component technologies that needs further study is optical switching technology. It will require higher speed (nanoseconds rather than milliseconds), large dimensions (comparable to label-switched lightpaths), wavelength-insensitivity, and lower insertion loss.

B.3.5 Long-Haul Networks

There are several challenging research topics in this area. For example, what is the ultimate realizable bandwidth/distance? What are the optimized designs of fiber transmission medium that can greatly reduce the nonlinear and linear impairments? What would be the desirable modulation formats to deliver robust data over longer distances? What is the impact of

Electronic Dispersion Compensation (EDC) using electronic signal processing? Is EDC a real cost savor or is it another electronic gadget that will eventually fade in time?

B.3.6 Network Synchronization

The atomic clock on a chip can simplify the problem of clock synchronization. In a Synchronous Digital Hierarchy (SDH) network or in a Synchronized Optical Network (SONET), there is a cesium clock (2.048 MHz) that functions as a "master clock" or primary reference clock (PRC). This clock is distributed in the network with the data signals and regenerated in the network nodes in "slave clocks". This clock regeneration is never completely prefect; rather each regenerated clock will have variations in frequency and phase. The more nodes passed "en route", the less stable the clock will be. This problem may be alleviated by using an "atomic clock on a chip" instead of derived clock sources. This is an area that should be explored.

B.3.7 Burst-Mode Receivers

Burst-mode receivers are important requirement for both FTTX in the access networks and for optical label and packet-switching metro and core networks. Data rates up to 10 Gbps are necessary; and design and fabrication of such receivers with large dynamic range that can accommodate variation of power between packets of the order of 18 dB is necessary. Also the receiver should acquire the clock in a few nanoseconds (e.g., not more than 20 nanoseconds) between packets.

Since optical networking is a new topic, there is a general lack of understanding as to how to compare different optical networking architectures and protocols. More specifically, there are questions as to (a) what are the traffic characteristics (which in turn depend on the existing and foreseeable applications to be run on optical networks), e.g., is the traffic smooth, of constant bit-rate type, or bursty of self-similar type; (b) what are the appropriate performance metrics to be used, e.g., is request blocking probability in a circuit-switched network a fair measure, when comparing different protocols or one should consider using something like revenue/profit; and (c) how can one compare different switching paradigms such as circuit switching and burst switching under common assumptions and using common performance metrics?

B.3.8 3-R All-optical Regeneration

Multi-channel amplification and 3-R regeneration are important techniques for all-optical transport networks. This will replace the current prevailing optoelectronic regeneration at the routers and switches. 3-R regeneration will speed up the deployment of optical burst and optical packet switching in the core network. The challenging related research topics are:

- All-optical 3R clock recovery and data regeneration
- Burst mode receiver, with large dynamic range
- Preamble-free data recovery
- End-to-end synchronization without SONET-like clock hierarchy.

B.3.9 Optical Buffer Memory

The objective of this research is to develop variable-delay optical buffers and optically transparent, scalable, and broadcast/multicast-capable optical switch fabrics. Optical buffers are vital components in optical packet switches, and they are responsible for packet synchronization, contention resolution, and traffic shaping. Existing optical packet switch (OPS) buffers suffer from many drawbacks that limit their practical usefulness. These include a limited range of delay values due to noise accumulation, fixed buffering capacity, and large physical volume as a result of using too many redundant delay lines. Recently, two different approaches of optical buffer architecture have been reported to solve these problems. The first is based on a novel folded-path design and high-speed ON-OFF switch/reflector, and the other utilizes “slow light” modulators made of photonic crystal bandgap devices. This buffer design should not impose a limit on the packet size, and the optical delay is dynamically reconfigurable even though the packet is already stored in the buffer.

The flexibility and scalability of the optical buffer design have to be investigated through both theoretical and experimental studies. Hence the range of delays supported by the buffer should be very wide or the delay granularity should be made to be very small.

B.3.10 Integration of Broadband Optical/Wireless Access

There is strong interest in providing both broadband wireless and wired access services in a single hybrid optical-wireless network. In this architecture, one can combine the advantages of mobile, point-to-multipoint access technology provided by an ultra-broadband wireless access network and the high-bandwidth, highly-reliable connection provided by an optical access network. Optical millimeter-wave generation and all-optical up-conversion are key techniques in realizing the desirable dual services using radio-over-fiber (ROF) systems. Recently, a few new schemes for realizing these functions have been reported. Among them, the simplest and the most accurate scheme to generate optical millimeter wave at high frequency up to 40-60 GHz employed external intensity modulation scheme. Researchers have demonstrated the millimeter-wave generation using external modulator such as LN-MOD-based on double-sideband (DSB) or single-sideband (SSB) modulation scheme.

Optical millimeter waves can be generated by several all-optical up-conversion schemes such as utilizing nonlinear fiber based on FWM or XPM, EAM-based on cross-absorption modulation, and external modulation based on dual (single)-band or optical-carrier suppression modulation. No matter what kind of all-optical up-conversion scheme one chooses, a part of the baseband signal still exists in the whole electrical spectrum after all-optical up-conversion. The LO frequency for an all-optical up-conversion scheme based on FWM in fiber is milimeter wave (e.g., 40-60 GHz) and the base-band signal (original signal before up-conversion) is a 1.0-2.5 Gbps NRZ regular signal. For wireless transmission, one need to use the high-frequency band, while the baseband signal is suppressed by a band-pass electrical filter with a center frequency near 40 GHz. One can explore novel ROF network architectures to use the baseband signals for direct optical access at 1.0-2.5 Gbps using low-cost components. The novel network architecture consistsing of the up-converted optical millimeter wave signals is divided in two parts. The first part can be detected by a high-speed receiver; then it is amplified by a bandpass electrical filter before sending to antenna on the ceiling of the rooms. The other part is directly sent to the plugs on building wall via optical fibers. One can use patch cord to connect the user units by optical fiber. Thus a low-cost receiver in the user unit can be used to directly detect the optical signal at baseband, while filtering out high-frequency signals. In this way, one can simultaneously provide the wireless and wired services in access networks in a single platform.

To realize this vision of providing wireless and wired services in a single integrated platform, one needs to develop RF front-end components including antenna, RF transmission line, amplifier, and local mixers at 40-60 GHz as well as all-optical up-conversion technologies for WDM optical signals originated from WDM-PONs.

B.3.11 National Testbeds

There is an ongoing national light rail consortium project that covers from the Atlantic coast to the Pacific coast in the United States. It aims at providing tens of WDM channels at 10Gbps to link universities, national labs, and supercomputer centers. But it is basically a circuit-switched network relying on MPLS and GMPLS router/switch technologies. We need to establish a new national testbed for optical packet-switched networks based on optical packet/label-switching technologies.

Appendix C:

Research Issues in Network Control and Management (Software)

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We started by defining two terms -- "optical networking," and "control-plane functionality" -- to focus the scope of our discussion. The definition of optical networking has progressively evolved over time. We can distinguish three generations of optical networks as discussed in Appendix A:

A definition for the term "**control-plane"** offered at the discussion is as follows: "Infrastructure and distributed intelligence that controls the establishment and maintenance of connections in the network, including protocols and mechanisms to disseminate related information, and algorithms for engineering an optimal path between end points." A goal of many control-plane researchers is to migrate many of today's centralized management-plane functionality in the five classical topics of network management, i.e., Fault, Configuration, Accounting, Performance, and Security (FCAPS) management, down to the control-plane software in network switches for a distributed implementation. Implementing these functions in the distributed control-plane rather than in centralized management plane should have the following benefits:

- A speedup of reaction time for most functions
- A reduction in operational time and costs
- More agility in the behavior of the optical network, e.g., dynamic sharing of link bandwidth
- Allow for a scaling of these networks to achieve a global reach.

As an example, consider a "link-down" indication. In current optical networks, automatic protection switching (APS) techniques are used for a 50-ms switchover from the primary path to a protection path when a link failure is detected. The cost of such protection schemes lies in the extra capacity required for the protection circuits. Control-plane procedures are being developed to enable fast "restoration" whereby new circuits are set up dynamically in response to a failure event. This allows the service provider to have smaller amounts of extra capacity because spare capacity can be dynamically allocated in response to failures at different locations. This is unlike in protection schemes where the spare capacity is nailed up for specific protection circuits. Such procedures can thus be expected to yield significant savings in costs. Migrating some of the management functionality from a centralized implementation to a more distributed implementation provides network switches the capability to react quickly to the changing needs of the network operation, and therefore the optical network becomes more agile.

The Automatically-Switched Transport Network (ASTN) is often used to describe optical networks in terms of functional planes: Transport Plane (TP), Control Plane (CP), and Management Plane (MP). In early optical network deployments, the CP was absent and the MP was used as the provisioning tool. More recently, the CP in optical networks is gaining the role of provisioning instrument, while the MP in optical networks is moving from being a provisioning instrument to a monitoring and supervision instrument.

In addition, services desired by customers of optical networks, which are requested on demand from the CP, are becoming increasingly complex (far beyond pure connectivity services). Instead they are getting closer to application abstractions, e.g., grid services, interactive applications, storage services, and triple-play services (voice, data, and on-demand video). We shall address the needs of provisioning for such services and consider the role of the control plane for transport provisioning versus for service provisioning.

The boundary between access network (client network) and metro-core network (ASTN) can become the service-supportive regions for service provisioning. An evolution of the ASTN, provisionally named Service-oriented ASTN (SO-ASTN) can be conceived as having an extra plane, namely Service Plane (SP), above the Control Plane and interworking with it through an interface. The SP has masking functionalities (virtualization and adaptation) for the translation of complex service requests into simple connectivity services, served by the standard MP+CP+TP known ASTN architecture. The intelligent edge between client (networks) and the metro/core network can be equipped with distributed cooperative SP components. An example of such a distributed SP realization is Grid middleware, such as the Globus toolkit, and corresponding server nodes deployed in client and/or core networks. An important issue to investigate is also the possible functional separation of a Service Provider and a Transport Provider.

With the above clarifications on CP vs. MP and CP vs. SP, we can define control-plane functions to include:

- Routing, both intra-domain and inter-domain
- Automatic topology and resource discovery
- Path computation
- Signaling protocols between network switches for the establishment, maintenance, and tear-down of connections
- Automatic neighbor discovery
- Local resource management to keep track of available bandwidth (and buffer in connection-oriented packet switches) resources on the switch’s interfaces.

The above definition of control-plane functions, as a set of functions needed for creating agile, large-scale connection-oriented networks, highlights the need for such functionality in second-generation optical networks (as defined above). This is because the OADMs and OXCs identified as the switching components in this generation of optical networks are circuit switches, which means the networks created using these switches are necessarily connection-oriented.

In our classification of optical networks, we gave examples of connection-oriented networks in all three generations of optical networks. Therefore control-plane problems are indeed important to create dynamic large-scale optical networks. We note that **all-optical** WDM-based second-generation networks create additional constraints in the control-plane problem definition not seen in first-generation connection-oriented optical networks. We list these additional considerations in **Section C.1**.

Given that first-generation optical networks are already deployed, and this set itself includes different types of connection-oriented networks, even before we can interconnect second-generation all-optical WDM or SDM optical networks into the already deployed first-generation networks, we need to address the question of how to control heterogeneous connections, i.e., connections that traverse different types of connection-oriented optical networks. This problem is addressed in **Section C.2**.

Much attention has been directed at the low configuration speed of MEMS devices (on the order of a few milliseconds), but the long call-processing delays (often in hundreds of milliseconds) to handle signaling requests for bandwidth are ignored. **Section C.3** raises this issue and provides motivation for decreasing call-processing delays.

In **Section C.4**, we describe the importance of the control plane in bridging the gap between optical networking technology and users of this technology. We make the case that current applications for optical networks are limited because the end points of an optical network are typically IP routers, and we propose ways to extend services of these networks to the end users' hosts. This section addresses both end-user and service-provider applications of optical networks.

Other control-plane problems, such as the management of the control-plane, decoupling transport and service provisioning, pricing and potential shortcomings of GMPLS control-plane protocols, are addressed in the remaining three sections: **C.5 through C.8.**

C.1 Control-Plane Problems Specific to All-Optical WDM Networks

The second generation of all-optical WDM optical networks has a unique set of control-plane problems. We classify these into physical impairment related problems, such as dynamic management of physical impairments and impairment-constrained routing, failure localization, and problems dealing with multi-granular optical switching technologies.

C.1.1 Physical Impairment-Related Problems

There are techniques for handling signal impairments at the physical layer (i.e., on links between two OADMs/OXCs or between an endpoint of the optical network and an OADM/OXC. Optoelectronic regenerators can be located on a per-channel basis at selected network nodes. Networks using such regenerators are termed "almost-transparent," "managed-reach networks," "islands of transparency," and "translucent networks." Alternatively, one may use dynamic impairment-management techniques in-line (e.g., all-optical regenerators and other optical means of impairment compensation), or at optical transponder interfaces (e.g., electronic mitigation of impairments). In addition to such physical-layer impairment-management techniques, the network designer may use certain Power, Routing, and Wavelength Assignment (PRWA) algorithms that take into account the signal impairments and constrain the routing of wavelength channels and their power assignment according to the physical characteristics of the optical network paths. Routing in communication networks involves the identification of a path for each connection request between the source and destination nodes. Existing routing approaches find a path by minimizing a certain (normally additive) cost parameter such as the number of hops or the length of the connection. Such routing algorithms typically assume that physical-layer link characteristics such as bit-error rate (BER) are fixed values. These algorithms focus on optimizing objective measures such as network throughput, aggregate call-blocking probability, or average packet delay for expected traffic loads assuming that the network topology, with physical link capacities and error rates, are fixed (given) parameters. However, in transparent and managed-reach optical networks, network-layer metrics, such as network throughput or call-blocking probability, can be improved if routing algorithms not only include traffic load as input parameters, but also physical-layer parameters, such as BER, OSNR, Q-factor, etc.

The challenges in the impairment-constraint-based routing include the following:

- Modeling different types of physical impairments and their interplay, and reflecting their impact on overall network performance.
- Developing an integrated framework that connects and associates physical impairments (e.g., chromatic dispersion, polarization mode dispersion, amplifier spontaneous emission, crosstalk, nonlinearities) and networking aspects (e.g., traffic blocking, utilization of resources, end-to-end delay, throughput). This framework should provide integration of PRWA and physical transmission with switching models in order to enable the assessment and optimization of the combined physical and network effects.
- Developing a mechanism that allows impairment information to be exchanged between the network switches, e.g., by incorporating such information into the routing protocol.
- Developing optical impairment-monitoring tools.

C.1.2 Failure Localization

We define failures to include both faults and attacks. Failure management has become a very important issue for network operators, whose goal is to offer services over a secure and resilient network that is capable of preventing attacks, as well as localizing and restoring the network from both faults and attacks. Hence, an efficient failure localization method is needed. Existing methods are optimized to locate failures in opaque optical networks, which allow monitoring of the optical signal at every regeneration site. However, to the best of our knowledge, no method exists today that performs failure localization for transparent optical networks. Such networks are more vulnerable to failures than opaque networks because failures propagate more easily without the isolation protection offered by optoelectronic conversions. Failure localization or identification is based on the received alarms by the network control and management system. Failure management relies on the information collected from network monitoring equipment. Such monitoring equipment supervises the signal after tapping, and therefore, does not adversely impact the optical signal transmission.

We need robust failure-location algorithms that can localize single and multiple failures in transparent optical networks under non-ideal conditions resulting from the reception of false and/or lost alarms, and being limited in the number of available monitoring points. Towards developing such algorithms, a thorough understanding of existing optical monitoring devices must be developed, and a balance between monitoring complexity and efficient failure localization must be achieved. Research on quantum cryptography offers interesting avenues for securing optical networks against attacks.

C.1.3 Multi-Granular All-Optical Switching Technologies

Another control-plane issue that arises in all-optical WDM networks is due to the multi-layer switching hierarchy in such networks. Up to a certain limit, all-optical forwarding is multi-rate, which is not the case for electrical forwarding. Similarly, an electrical repeater-regenerator is single-rate whereas an optical amplifier is multi-rate. For data rates up to 10 Gbps, transparent connections (without electrical regeneration) up to 2000 km are achievable, depending on the quality of the optical fibers. Thus, is it possible to aggregate electrical flows or connections into transparent lightpaths. Transparent lightpaths may in turn be aggregated into wavebands, wavebands being physically aggregated on to the same optical fiber link. The emergence of the concept of multi-granular all-optical switches has resulted in the problem of determining how to route connections through OXCs, waveband cross-connect (BXCs), and FXCs. Networks consisting of multi-granular all-optical switches have several new problems:

- how to efficiently manage the mapping between the statistical multiplexing nature of data arriving from (connectionless) electrical IP routers with the current circuit-oriented nature of the all-optical switches (OXCs, BXCs, FXCs)?
- which multi-layer model (peer, overlay, or augmented) is appropriate and what kind of information must be exchanged between the layers?

We generalize the problems described above to include both first- and second-generation optical networks in the next section.

C.2 Heterogeneity of Connection-Oriented Optical Networks

As noted in the introduction, all three generations of optical networks will include connection-oriented networks. Many first- and second-generation connection-oriented networks are already deployed. However, the heterogeneous nature of these connection-oriented network technologies is often hidden as a result of its common use in the construction of IP data networks. By design, IP networks present a common bearer-service protocol, which hides the differences between the technologies used in the multiple connection-oriented networks that could be traversed on an end-to-end path. However, for a multitude of reasons, many emerging network applications now desire to have direct access to services of these connection-oriented networks.

These applications tend to require rate and/or delay/jitter guarantees, and hence cannot tolerate the non-determinism of such metrics on connectionless networks. Provisioning of rate- and/or delay-/jitter-guaranteed connections may also be advantageous based solely on economic reasons or for traffic engineering of IP networks. The result is an increasing desire to construct “hybrid” networks, which can provide both connectionless IP service along with connection-oriented (CO) services. Several research proposals, such as CHEETAH [1], DRAGON [2], UltraScience Net [3], HOPI [4], OMNInet [5], ORION [6], UKLight [6], SURFnet [8], and Canarie’s CA*net4 [9], are exploring ways to create and use such hybrid networks.

The recent period of network innovation has resulted in a wide range and diverse set of available CO network technologies. This includes SONET/SDH, WDM, IEEE 802.1p and 802.q Ethernet Virtual LANs (VLANs), and MPLS/IP technologies. All of these are finding application in the market place, and it is expected that the diversity in network architecture, design, and implementations will increase in the foreseeable future. In addition, new optical network technologies such as optical packet switching and optical burst switching are active research topics and may find their way into network infrastructures in the future. Hybrid or heterogeneous network configurations would again be crucial to allow for an evolution from current optical network technologies to future ones.

Besides developing the data-plane aspects of these different types of connection-oriented networks, standardization efforts in the Internet Engineering Task Force (IETF) have created a common set of control-plane protocols, for routing, signaling, and link management. These are commonly referred as Generalized Multi-Protocol Label Switching (GMPLS) control-plane protocols. For example, the GMPLS signaling protocol Resource reSerVation Protocol (RSVP) with Traffic Engineering (RSVP-TE) as specified in IETF RFC 3471, 3473, etc. builds upon the original RSVP protocol defined for Integrated Services ("Intserv") in IP networks (IETF RFC 2205), which is a form of connection-oriented IP service. Having a common set of protocols applicable to most connection-oriented network technologies used in practice today will result in implementation and administrator-training cost savings. With this set of GMPLS control-plane protocols, dynamic CO service is now possible, where calls requesting high-bandwidth connections can be set up and released dynamically with no manual intervention. Other standardization efforts defining architectures and protocols to create dynamic CO services include activities in the Optical Internetworking Forum (OIF) and the ITU-T Automatically-Switched Optical Networks (ASON) group.

The goal is for this new class of dynamic CO services to be offered across multiple domains and heterogeneous network technologies. This is in contrast to the current provisioning of CO services, which typically involves the establishment of a connection across a single network technology administered by a single provider. These emerging applications will want to "dial-up" variable bandwidth pipes between various end-point locations. Additionally, connection timescales will become increasingly shorter and unpredictable, e.g., grid computing. Likely, these end-points will not reside in a single domain or possibly even within a single carrier's network. Moreover, the connections will likely traverse CO networks of many different technologies (packet-switched, such as MPLS, TDM, WDM). This opens up a host of issues relating to provisioning end-user demands (packet or circuit-based) across domains comprising vastly different technologies.

Recent research and development efforts have focused on technologies and provisioning algorithms for a specific type of CO network, e.g., WDM, SONET/SDH, and others. The past few years have seen some progress in developing and implementing interworking mechanisms for the data plane of these different types of CO networks. However, the pressing concern now is to address the challenges of translating these gains in real operational networks. A key missing element is the control-plane interworking aspect. Some of the key sub-topics to be addressed include inter-domain routing extensions between different types of CO networks, distributed path-computation algorithms across heterogeneous CO networks, and distributed bandwidth-management algorithms. Many of these issues remain largely unaddressed, both from a research perspective and in the context of application to actual network environments.

Toward resolution of these issues, it is helpful to identify some terms to describe the various dimensions of network heterogeneity. We can describe this heterogeneity as "multi-X", i.e., Multi-Service, Multi-Layer and Multi-Technology, Multi-Domain, Multi-Provider, and Multi-Vendor networks. These terms are all typically being used in modern networks. Below is a short explanation of these terms.

- **Multi-Service:** Within a single network, there are demands with diverse traffic parameters, such as bandwidth, duration, etc., and quality-of-service (QoS) requirements, such as delay, jitter, loss, etc.
- **Multi-Layer and Multi-Technology:** A multi-layer protocol stack results from the use of "inner" connections between two network entities as links in "outer" connections. These are inevitable given the multiple types of CO network technologies (i.e., Multi-Technology). For example, we may start out by establishing an MPLS Label-Switched Path (LSP), and encounter a SONET network en route. We would then need to establish a SONET circuit through the SONET network and use this as a link in the outer MPLS connection. There are multiple models for creating such connections, namely overlay, augmented, and peer interconnection models. An area of study is Multi-layer Traffic Engineering (MTE), which combines functions in the various layers to optimize performance and QoS. For instance, in an IP-over-ASON scenario, this encompasses the (re)configuration of the logical topology (i.e., IP network topology) network, by dynamically setting up and tearing down optical lightpaths, together with the routing of the offered IP traffic demand over the logical topology.
- **Multi-Domain:** This term refers to horizontal structure of networks. For administrative or scalability reasons, the network consists of horizontally interconnected parts.
- **Multi-Provider:** This refers to having more network operators and service providers within a single network. The networks of different operators and providers can be either horizontally interconnected or vertically overlayed/interconnected.
- **Multi-Vendor:** This refers to having components of the network, such as network switches, delivered by different equipment vendors.

Definition of multilayer resilience schemes to decide what type of scheme to use and at which layer to implement the scheme is needed. This could be application-specific. Also, we need to define a method to coordinate between resilience schemes implemented at different network layers or in different network domains.

Realization of this new class of CO services will require the development of new technologies, architectures, protocols, and software. Additionally, this service provisioning must include features for Authentication, Authorization, Accounting (AAA) and scheduling (book-ahead) to provide for a viable usage model.

C.3 Performance of Control-Plane Protocol Implementations

Control-plane protocols, such as signaling and routing protocols, are typically implemented in software. While performance of such implementations is probably not critical for routing protocols, this is not the case with signaling protocols. Signaling protocols are the key mechanism used to request rate-guaranteed connections as needed and to release them when done. If implementations of the protocols are not performance-oriented, i.e., call-processing delays are not kept to a minimum or call-handling throughputs are not maximized, then the use of connection-oriented optical networks is limited to applications that require long-held connections. For example, if call-processing delay at each switch is 200 ms, then a connection set up through five switches minimally incurs a 1-second call-setup delay. Since the bandwidth held at upstream switches during the setup of the connection lies unused until the connection setup is complete, this 1-second overhead should be amortized over the large call-holding time to maintain high link utilization. This limits applications that can use connections. In the eScience community, large file transfers are touted as applications for high-speed optical circuit-switched networks. However, the definition of “large” quickly shrinks as data rates increase. In this application, call-holding times decrease as data rates increase, which means the cutoff file size beyond which the call-setup delay becomes a small enough overhead to justify the use of connections becomes larger and larger. This in turn limits the usability of high-speed optical connection-oriented networks for file transfers, because fewer and fewer files will be larger than the cutoff size.

Therefore, research projects aimed at improving signaling protocol implementations, e.g., hardware-accelerated implementations, are important to expand the scope and usefulness of optical connection-oriented networks.

C.4 Applications Resulting from Optical Control-Plane Advances

Optical control-plane research lies between optical networking hardware research and applications. Just as optical networking hardware advances are needed to put into use advances in optical devices (such as tunable lasers and fast switching devices), similarly, control-plane advances are needed to enable the use of optical networking hardware (such as OADMs, OXCs, OPS, and OBS). Optical control-plane research is thus key to bridging the gap between applications and optical networks.

The two applications most commonly noted as being enabled by control-plane advances are rapid provisioning and fast restoration. Rapid provisioning is used to automate many of the steps created in leasing high-bandwidth circuits from service providers. Most commonly, this application is expected to be triggered by enterprise network administrators and data communication service providers who need high-speed connectivity between IP routers or other types of network switches. Fast restoration is used to restore provisioned circuits between IP routers or other types of network switches when failures occur. Triggers for fast restoration are clearly not likely to happen often.

Bob Metcalfe, inventor of the Ethernet, noted the total value of a communication network grows with the square of the number of devices or people it connects. This makes us recognize the need to increase the number of endpoints (and correspondingly applications) that request dynamic CO services. The GMPLS control-plane protocols are designed to create scalable networks with large numbers of endpoints. Being based on the Internet architecture, which clearly proved to be scalable to a global-sized internetwork, these protocols will be key to rapidly growing the number of users of dynamic CO services. With the availability of connection-oriented services in already deployed Ethernet switches in LANs (through their implementation of the IEEE 802.1p and 802.1q standards) and the availability of VLAN features on end host NICs, it is now possible to extend dynamic CO services to desktops.

Combining VLAN capability in LAN switches with MPLS capability in IP routers deployed in Internet2, we already have a widely deployed base on which to experiment with dynamic CO services. This offers a base on which to develop end-host applications for dynamically requested rate-guaranteed connections. Such efforts will translate to second-generation optical networks, since these networks are circuit-switched and the switches are increasingly equipped with GMPLS control-plane protocols.

We address end-user applications and service-provider applications in the two subsections below.

C.4.1 End-User Applications

Mobile applications: Control-plane protocols will be critical in enabling mobile applications. Aggregating a large number of wireless users will result in a need for high-bandwidth wired networks for which optical networks are ideal. This implies a need to interwork optical networks and wireless networks. As an example, consider hundreds of fast-moving users in a train wanting real-time broadband network connections (see Section A.5.2). To meet this need, a large number of antennas (e.g., one antenna per 100 m) may be placed along the railway tracks, providing wireless access at high-band frequencies (e.g., 60 GHz) through antenna(s) on the train. Due to the very frequent handovers between the fixed antennas, dynamically reroutable connections through the wired network (to the fixed antennas) will be crucial. Moreover, special measures must be taken to limit the transient affects during handovers.

Grid applications: Some high-end Grid applications place unique and challenging demands on the optical network infrastructure. These applications assume a dynamic on-demand use of end-to-end optical networking resources, global transfers of very large data sets across large distances, coordination of network resources with other vital Grid resources, such as CPUs and storage servers, advanced reservations of networking resources, deterministic end-to-end connections (with low jitter and low latency), connection timescales of a few microseconds to long-lived lightpaths, and near-real-time feedback of network performance measurements and resource availability to both the applications and middleware. To meet these challenges, the optical networking community, in conjunction with the Grid community, must rethink the role of intelligent optical control plane. Today's networks place the role of creating an end-to-end optical connection between two networks as a manual function carried out by an operator from a centralized management application. This is an isolated task requested by IT personnel where the end-points of the connection are some form of edge-network device (e.g., edge-router) and the duration of the connection is in terms of weeks, months, or years. In contrast, these new applications are making on-demand requests for end-to-end optical connections where the endpoints as workstations, PCs, clusters, sensors, and instruments rather than network elements, and the durations of these connections are based on the particular application's requirements, ranging from microseconds to hours/days. The application's request for such network resources must also be coordinated with other required resources such as CPU and storage. Control-plane interactions with applications and Grid middleware represents a paradigm shift for both the optical control plane and application development. Only through the combined efforts of the two communities, e.g., in the form of vertical integration, can such an infrastructure (composed of both hardware and software) be developed.

Let us look at a typical scenario of a new-generation Grid application, exhibiting intelligent and adaptive behavior within a Grid environment. Suppose an astrophysics researcher submits a black-hole simulation via a portal somewhere on a global Grid. Using an abstract, application-oriented API, such as that provided by the Grid application toolkit (GAT), the researcher's application will contact an underlying Grid information service, to determine where to launch the requested simulation. Once the initial target is decided, the application migrates the code to the target and spawns the simulation; the newly-spawned code then registers the new location with the Grid information service. As the initial simulation runs, the application may perform one or more of the following scenarios:

- Large amounts of data (tera- and peta-bytes in size) result from the simulation, which require storage, either local to the simulation node or at geographically dispersed locations. If remote storage is necessary, then the application itself creates an on-demand network connection and streams data to the site.
- The simulation application might perform near-real-time analysis of the output data and detect a black-hole event horizon, which suggests that the parameters and conditions of the simulation are closer to a detection of a black hole. This detection could spawn a new finer-grain simulation at a remote computation cluster available on the global Grid.
- A slow part of the simulation runs asynchronously, so the application might spawn that part separately.
- New and more powerful resources could become available (the application becomes aware of newly-available resources from the feedback loop with Grid resource management middleware), so the simulation might migrate to a faster cluster.
- An end-user could interact with the simulation and perform computational steering, i.e., interactively control the computational process during runtime.
- Powerful visualization tools are often required to graphically display the data.

The compute resources in the above scenario are assumed to be geographically dispersed and interconnected via high-capacity optical networks. In order for the black-hole simulation application to perform the above scenarios, the application must have access to changing resources within the Grid infrastructure as well as on-demand/advanced reservation access to those resources including the rapid creation and deletion of end-to-end optical connections. Grid middleware provides a near-real-time feedback loop of information about various resources so that applications can make intelligent and dynamic decisions on how best to exploit them. Under these conditions, the applications are no longer limited to local resources or available resources at the time of initiation, but rather the application can dynamically adapt to the changing resources within a geographically-distributed Grid infrastructure. The network control plane plays a key role in providing this vertical integration.

Network requirements for these applications include:

- High bandwidth pipes along very long distances – terabyte transfers, petabyte, etc.
- Network resources coordinated with other vital Grid resources – CPU, storage, and visualization displays.
- Advanced reservation of networking resources.
- Deterministic end-to-end connections – low jitter, low latency.
- Applications/end-users/sensors/instruments requesting end-to-end network resources and optical networking resources on demand for short periods of time.
- Near-real-time feedback of network performance measurements to the applications and middleware.
- Exchange data with sensors via other physical resources.
- Destination may not be known initially, rather only a service is requested from the source.

Other applications: There are several other end-user applications that can take advantage of high-bandwidth end-to-end connections. These include data mirroring, storage area networks (SANs), remote surgery, interactive gaming, high-quality video telephony (with multiple remote-controlled cameras), video conferencing, 3D virtual communities and tele-immersion.

C.4.2 Service-Provider Applications

Rapid Provisioning: Control-plane functionality is used to reduce the network operator's Operational Expenses (OPEX) by initiating the provisioning of a connection at one end and allowing the GMPLS signaling protocol, RSVP-TE, or a comparable protocol to execute its connection setup procedure in a distributed manner to rapidly provision the connection. This application can be used in traffic engineering of IP networks.

Virtual Private Networking (VPN) Services: Carriers using optical networks to provide VPN services look for technologies that lower overall operational expenditures. Meanwhile, customers of VPN services would like to see a wider range of "agile" services, priced according to bandwidth and stringency needs. It is here that the application of the GMPLS control plane across multiple technology layers and domains will play a vital role.

To date, many research studies have looked at the cost and complexity of various services such as bandwidth-on-demand (e.g., wavelengths-on-demand), fractional Ethernet (via next-generation SONET/SDH), etc. However, by and large, most of these studies have considered the provisioning of these services over homogeneous technology domains/layers. Given the fact that real-world services will traverse many different technologies (layers) and domains, further extension of the above services needs to be considered appropriately, e.g., related signaling, routing, and path computation/grooming issues, etc.

Recently, for many large customers, the notion of "virtual infrastructures," i.e., Layer 1 (L1) VPN has become appealing. This topic is receiving much attention within both the IETF and ITU-T (SG-13) standards bodies. Indeed, a service offering such possibilities can potentially offer some key advantages for both clients and carriers alike. Namely, carriers can simply assign a wide set of network resources (wavelengths, timeslots, etc.) to customers in a dedicated or shared manner. This allows customers to build their own "topologies" and effectively out source detailed provisioning decisions to carriers. Customers can thus preclude the sizeable costs and delays associated with building and maintaining real physical optical or TDM infrastructures. Instead, they can focus on developing new services to interconnect a wide range of end-user sites and avoid having to purchase multiple point-to-point leased-line circuits. Although L1 VPN concepts have seen much progress over the past year, detailed implementation, algorithmic, and performance aspects have not yet been considered (particularly regarding the adoption of a GMPLS-based control plane).

A host of issues need to be considered for L1 VPN services to mature further. For example, some key topics include the design of novel resource-provisioning algorithms (dedicated/shared across both TDM and WDM layers), extension and analysis of distributed routing protocols (security, abstraction), distributed L1-VPN signaling and path-computation algorithms. Moreover, follow-on implementation and test-bed trials are also needed to provide much-needed "prove-in" value. Also, the complexity introduced (at the GMPLS control plane) to support L1-VPN operation needs to be studied in order to meet desired operational expenditure goals.

C.5 Management of the CP

Currently, operators are reluctant to adopt a completely automatic distributed CP with general-purpose abilities. The reasons are (i) the absence of a real business plan for it, and of a clear evidence of OPEX savings with respect to managed networks, and (ii) operators want to manage the control plane and keep it supervised in its automatic operation. In this area, a CP information model is needed for the benefit of the MP. Specifically, a comprehensive information model (IM) must deal with two different aspects of CP management: an IM is needed for the entities representing the CP operation itself (i.e., the CP network with CP nodes) and another IM is needed for the entities representing the TP connectivity resources as presented by the CP to the MP. With respect to the latter model, the correct level of abstraction for managing the TP is needed (e.g., modeling the switching capabilities), different from the typical information modeling in use for modeling the TP nodes when directly seen by the MP (where any framing termination is modeled).

C.6 Decoupling Transport and Service Provisioning

End-user services are evolving rapidly with respect to connectivity services (those that typically can be requested through a user-to-network interface (UNI) (e.g., OIF UNI or GMPLS UNI). In order to allow an independent evolution of end-user services (grid, triple play, etc.) and a masking of the transport details to applications, we envision the introduction of a structured plane, called "service plane" in the metro/core edge nodes. The edge nodes are provided with extra features that enable them to "understand" client connectivity requests expressed in coarse terms more close to the application context. This permits a decoupling of service delivery from network-related issues and to rapidly create and modify services, and thus to tailor them to customer or application needs.

In view of the above considerations and general architectural objectives, the following provisional list of new facilities may be available at the Service UNI (S-UNI), as opposed to a standard UNI: the capability of setting up LSPs and VPNs of any order, even if not issued by the customer edge node, the capability of handling interactive requests for complex information about the status of the ASTN (e.g., a request for topology information among specified nodes, not only connectivity state queries), and many others. The resulting architecture should be conceived in terms of functional blocks and interfaces, and should be open to different implementations from a technological (hardware and/or software) point of view.

C.7 Pricing

Connection-oriented networks offer the possibility of gathering data on call-holding times. Models based on per-unit-time pricing are well understood in telephony networks. Such models can be extended to include varying bandwidth levels. This potentially makes usage-based pricing more feasible than in today's connectionless Internet. There are opportunities here for interesting pricing models.

C.8 Other Control-Plane Issues

Questions were raised about studying alternative control-plane solutions, i.e., solutions other than GMPLS control-plane solutions. Cited examples include Just Enough Time (JET) [10], Just in Time (JIT) [11], and User-Controlled LightPath (UCLP) [12]. The complexity of GMPLS control-plane protocols was considered a handicap. A solution offered was to define subsets of the GMPLS control-plane protocols for hardware-accelerated implementations.

Questions on addressing control-plane protocols in relation to programmable networks, active optical networks, and access networks were also raised.

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Workshop on Key Issues and Grand Challenges in Optical Networking

Jointly organized and sponsored by ePhoton/ONe, NSF and COST291

Albert Borschette building, 36, rue Froissart, Brussels
27.06.2005-28.06.2005

Chairs
Fabio Neri and Biswanath Mukherjee

Technical and Organization Committee

- Fabio Neri
- Mike O Mahony
- Ioannis Tomkos
- Piet Demester
- Christoph Gauger
- Slobodanka Tomic
- Biswanath Mukherjee
- George Rouskas
- Arun Somani
- Malathi Veeraraghavan
- Chunming Qiao

Final Agenda

Monday, June 27, 2005

8:00 – 8:55 am: Registration
8:55 – 9:00 am: Welcoming Remarks,
- Slobodanka Tomic

9:00 – 10:45 am: Workshop Overview, Goals and Rationale
- Fabio Neri, "*Overview of ePhoton/One*"
- Biswanath Mukherjee, "*Review of Workshop Goals*"
- Admela Jukan, "*On Opportunities and Challenges in International Research Collaborations*"
- Jorge Pereira, EC, *"EC Objectives and Research Programs"*
- Afonso Ferreira, EC, *"COST Programs"*
- Discussion, moderator Fabio Neri

10:45 – 11:00 am*:* ***Coffee Break***

Current status of optical networking R&D, *chair Biswanath Mukherjee*
11:00 – 11:30 am: European Perspective
- Piet Demester, "Success stories: IP NOBEL, STREP Lasagne GEANT2"
- Ioannis Tomkos, "COST 291"

11:30 – 12:00 am: US Perspective
- George Rouskas, "NSF-Funded Projects"
- Malathi Veeraraghavan, "Testbeds"

12:00 – 12:30 am: Japanese Perspective
- Ken-ichi Kitayama, "Activities of Photonic Internet Forum of Japan"

12:30 – 2:00 pm: ***Lunch Break***

Key Notes from Provider and Vendor Perspective*, chair Christoph Gauger*
2:00 – 2:30 pm: Andreas Gladisch, "The Patchwork of Optical Networks"
2:30 – 3:00 pm: Martin Zirngibl , "A Vision for Scalable Optical Networks For Bursty Data Traffic"

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Outlining Key Issues and Great Challenges in Optical Networking
3:00-4:30pm ***European Perspective****, chair Fabio Neri*

- Ton Koonen, "Research directions in optical access networks"
- Dieter Jaeger, "Home Networks: A Future Market"
- Josep Prat, "High-density FTTH PONs and Electronic Processing"
- Piet Demeester, "Optics in access/aggregation networks: Consumer Grid and Wireless Internet Train"
- Alexandros Stavdas, "New Concepts for Dynamically Reconfigurable Optical Nodes"
- Mario Pickavet, "Migration towards hybrid optical networks: circuit & packet"
- Ioannis Tomkos, "Some thoughts on research topics for optical topics for optical networks"
- Fabio Neri, "Research directions in optical networking"
- Peter Tomsu, "Future Needs of Optical Networking"
- Christoph Gauger, "Integrated research to tackle challenges in photonic networking"
- Franco Callegati, "Research Directions in Optical Core Networks"
- Maurice Gagnaire, "Optical transparency in WDM long-haul networks: myth or reality?"
- Piero Castoldi, "Service-oriented optical networks"
- Tibor Cinkler, "On Routing, Traffic Engineering and Resilience over Optical Networks"
- Dimitra Simeonidou, "Applications-Networks Convergence: Implications on Optical Network Technologies"
- Branko Mikac, „"
- Pierluigi Poggiolini, „"

4:30 –4:45 pm*:* ***Coffee Break***

4:45 – 6:15 pm: ***US Perspective****, chair Biswanath Mukherjee*

- Martin Zirngibl, "Why we Love our DARPA Projects"
- G. K. Chang, "Challenges for Optical Packet Switching Networks"
- Loukas Paraschis, "Technologies and Architectures that Improve Optical Network Operations and Cost"
- Laxman Tamil, "Sub-Wavelength Switching in Optical Networks"
- Malathi Veeraraghavan, "Distributed scheduling"
- Admela Jukan, "Top 10 Life Saving Arguments on Why Optical Networking Research
- (still) Matters"
- Gigi Karmous-Edwards, "Network Research based on Vertical Integration"
- Tom Lehman, "Inter-Domain Control Plane Architectures for Optical Networks"
- Wu-chun Feng, "Optical Networking: An Initial Piece to a Larger Solution"
- Biswanath Mukherjee, "Network Architectures: Building Bridges with and Between Applications and Devices for Optical Networks"
- George Rouskas, "Thoughts on Research Challenges and US/EU Collaboration"
- Arun Somani, "Issues in Grooming and New Approaches"
- Suresh Subramaniam, "Research Opportunities and Challenges in Optical Networking Research"
- Jason Jue, "Research Challenges in Optical Burst Switching"
- Nasir Ghani, "Vertical/Horizontal Layer Integration and Infrastructure Virtualization"

Wrap-up and Further Steps
6:15 –6:30 pm*:* ***Closing comments for Day 1 and Goals for Day 2 (Workshop Co-Chairs)***

E1-NSF-COST Workshop, Brussels, 27.062005-28.06.2005

Final Agenda

Tuesday, June 28, 2005

8:00 – 9:00 am: Registration

9:00 – 9:15 am: Review of Workshop Goals & Day 2 Agenda
- Fabio Neri
- Biswanath Mukherjee

Exploring Key Issues and Great Challenges in Optical Networking

9:15 – 10:45 am: Focused Discussion on Network Architectures
- EU Lead: Piet Demeester
- US Lead: Arun Somani

10:45 – 11:00 am*: Coffee Break*

11:00 – 12:30 pm: Focused Discussion on Hardware Systems
- EU Lead: Pierluigi Poggolini
- US Lead: G.K. Chang

12:30 – 2:00 pm*: Lunch Break*

2:00 – 3:30 pm: Focused Discussion on Network Control and Management
- EU Lead: Dimitra Simeonidou
- US Lead: Malathi Veeraraghavan

3:30 – 3:45 pm*: Coffee Break*

Wrap-up and Further Steps

3:45 – 4:45 pm: Final Workshop Report – Strategies, Focus, And Delegation of Tasks.

4:45 – 5:00 pm: Closing comments (Workshop Co-Chairs)

E1-NSF-COST Workshop, Brussels, 27.06.2005-28.06.2005

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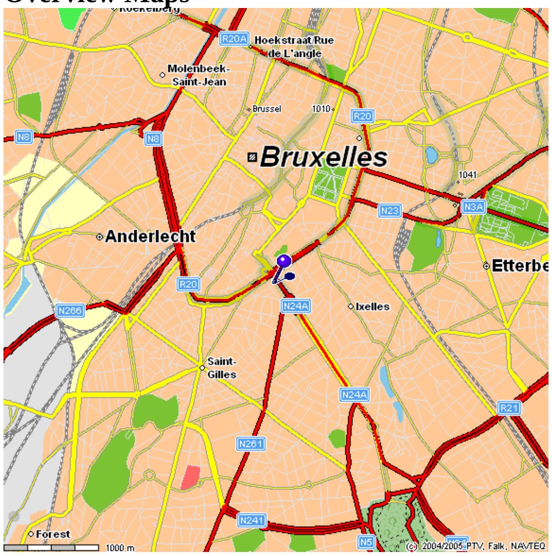
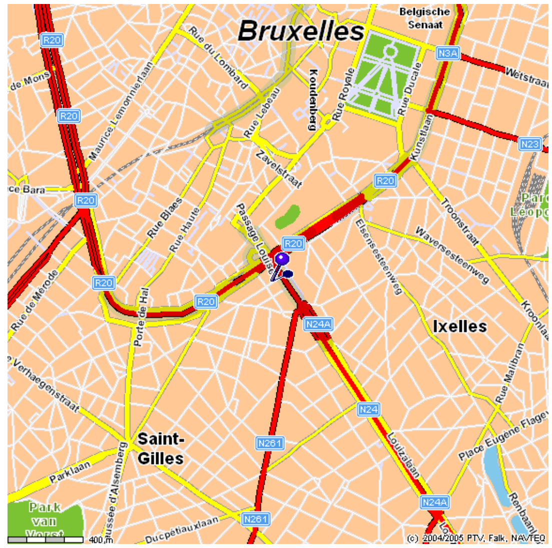
Dinner Location for Monday, June 27

Le Délire Parisien, 16 Rue Jourdan, 1060 Bruxelles, Tel. 02/537.06.94

Overview Maps





Local Map