G E N I

Global Environment for Network Innovations

Mapping a Future for Optical Networking and Communications

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Executive Summary

The content of the report reflects material generated as a result of a one year planning grant and input received at two workshops: a small-group workshop held in February 2005 and a larger community workshop held in April 2005. A list of the attendees at the two workshops can be found in Appendix I. All conclusions, however, are solely the responsibilities of the authors

Goals of the Study and Workshops: This report seeks to advise the National Science Foundation in crafting a vision for research in optical networking over the next five to fifteen years. Our goal is to provide input to multiple organizations within the NSF on the potential impact and opportunities of optical communications and networks towards NSF initiatives and areas of focus. These organizations within the NSF include but are not limited to the CISE and Engineering Directorates and within CISE we see relevance to the CCF and CNS divisions. Our goals include identification of areas of optical communications and networks that need the greatest attention and support and to reintegrate the optical communications and networking and the larger data communications and networking communities, to the benefit of both.

Impact and Relevance to NSF Re-Focused Research Programs and Experimental Facilities: Optical communications and network technologies have the potential for extremely high impact and relevance on new programs (and re-focused programs) and facilities set into place by CISE and Engineering. These new technologies will impact today's experimental networking facilities by offering a dynamic, reconfigurable, high-bandwidth networking medium not available with today's Internet networking technologies. By utilizing today's latest control plane technologies, these optical techniques can be integrated with other networking technologies to realize experimental facilities that will support research into networking techniques that will impact the next 10 to 15 years down the road. Additionally, re-focused research programs can be initiated to develop the next generation of optical network technologies that will impact experimental and real networks 5 to 10 years down the road. The impact and relevance will depend on the outcome of several questions including:

- Is there enough potential to make optical communications and optical networking a major research area within any or a combination of the NSF directorates, specifically within CISE and Engineering?
- What part of the proposed outcome of this study is directly relevant to CISE (CCF and CNS) and Engineering agendas?
- Can a re-focused research agenda be formulated to make progress in optics relevant in whole or in part to the CISE (CNS and CCF) agendas?
- How will the building of optical systems and networks directly contribute to the goals of new re-focused research programs and experimental facilities?
- How will new experimental facilities both benefit from optical communications and network technologies and enable new research to be performed that will impact the scientific understanding of how these new technologies enhance and advance networking research.

- How can a major research program in optical communications and networks be structured to bridge the existing gap between networking research and optical device research?

Problem Statement: The past fifteen years in optical communications research have been focused on the challenge of keeping pace with the fast growing demands for optical capacity. We have an opportunity to identify research directions that can have high impact on the field and community. With this opportunity in mind, there are four broad problem spaces in optical communications research.

- The first problem space is a re-examination of the fundamental questions that exist today in fiber optics: For example: What is transparency? How many bits can we signal per hertz? How do we build networks with capacities that utilize this bandwidth?
- The second problem space is how to enable the design and fabrication of densely photonic integrated circuits (PICs), from the device concept and design, to the use of these devices in real subsystems and networks. PICs will be the essential enabling technology to give fiber optics communications the economics, the adaptability and programmability and the improved ease of design-in, essential for any communications technology of the future.
- The third problem space is to understand how to partitioning signal and data processing and communications functions between optical and electronic technologies in order to optimize various factors like power consumption, bandwidth, throughput, latency, etc.
- The fourth problem is how to connect research in Internet driven and application driven architectures as well as new access architectures, to research in optical hardware by defining new "cross-layer" design principles that overcome today's boundaries between physical layer research communities, network architect research communities and application research communities.

Recommendations:
Our recommendations are geared towards investment in research agendas in three primary areas

(1) Foundations
(2) Engineering of devices
(3) Networking systems and architectures.

We also provide recommendations on design or structuring of funding programs at NSF to help realize the research agendas.

1 Introduction

Optical communication has been around in one form or another for 45 years with many concepts carried over from RF counterparts. Yet, by several measures, optical communications and optical networking are still young research fields. Their rate of innovation is high. Devices continue to increase in capacity faster than Moore's Law would predict. Many open issues exist about the performance and behavior of innovative network architectures and techniques.

Many still research questions remain open. Furthermore, the extension of optical communications to optical networks suffers a widespread perception that it is solely concerned with problems of building transport networks using transmitters, dumb switches and receivers: essentially low-layer networks that can intelligently move bits between switching points.

Optical communications and optical networking are areas rich in potential. The field is poised to enjoy major disruptive breakthroughs with the advent of higher levels of photonic integration, enabling photonic integrated circuits (PICs), embedded intelligence through integration with electronics and sharp cost reductions due to integration technologies.

This report seeks to address this situation by sketching a research agenda for optical networking for the next 15 years. In crafting this agenda we have sought to assess where the research frontier is now and what lines of research currently look most promising, without regard to how optical communications devices are currently viewed.

We also ask the following questions in this document

- Is it time to revisit optical communication and network research?
- Is there enough potential to make optical communications and optical networking a major research area?
- How can we bridge the gap between networking research and optical device research?

2 Where are we now and how did we get here

The driving force behind optical communications and optical networking research has been a continuous demand to improve the transmission capacity, configuration capabilities, and flexibility of networks based on fixed optical fibers, while sharply reducing operational costs. Meeting those goals has required a continuing series of innovations as fiber optics moved from single-channel use of a fiber, to wavelength division multiplexing (WDM) of point-to-point links to dense WDM transmission systems, to WDM and DWDM networks with multiple add/drop points. Technologies such as reconfigurable add/drop multiplexers (ROADMs), photonic crossconnects (PXCs) and wavelength tunable lasers have all been developed and then improved to meet these needs.

The result is transmission systems that can be provisioned automatically, provide flexible adjustment of bandwidth and restoration and self-healing at the network level. Additionally, the ROADM has enabled mesh networking that combines electronic grooming with transparent wavelength management in national scale networks. The focus has been on long haul networks, but there is increasing interest and utility to be found in putting these technologies to work in the metro and eventually local area networks.

A key roadblock to progress has been the separation of the optical communications community from the networking research community. Speaking broadly, the focus of the networking research has been on the development of innovative services built over packet-switched networks with research goals very different from the transmission network focus of optical research of the 80s and 90s. With the advent of RF wireless and cellular technologies, the networking community focused its effort on solving the interesting research problems of mobile, bandwidth limited system rather than the apparent fixed nature of fiber transmission systems.

Today we are in a situation where the two communities should exchange useful ideas and revisit topics of interest that bridge across the two communities. The networking research community is currently re-examining network architectures and (in large part due to the sense that we're underutilizing wireless technology) investigating how higher layer network protocols can take advantage of the capability of technologies such as optics. And the optical communications community has made tremendous strides in developing more flexible, capable optical communications systems that today seems to be on a path to chip level integration with the potential for integration with electronics and henceforth higher levels of intelligence. So there is an opportunity for synergy.

3 Today's Open Issues and Near Term (5-year) Opportunities

If one looks carefully at the near-term research issues, a few key themes appear:

1. *Expanding the media.* We need to investigate ways to expand the capacity of single mode fiber transmission systems using modulation techniques that go beyond simple on-off modulation. We also need to expand the capabilities of multi-mode and plastic fiber and free-space systems to achieve low cost, high bandwidth transmission alternatives.
2. *Increasing Transparency.* There are different levels of transparency: Protocol, format and modulation. First, we would like to build ever more reliable and richly connected optical networks – and protocol and format transparency is the easiest way to that goal, as greater transparency eases our ability to switch traffic from one fiber to another and, generally, increases our ability to dynamically reconfigure a network.
3. *Early Steps to Photonic Integration.* Combining simple photonic parts with silicon to develop basic programmable devices could achieve near-term results in modulation and in the creation of self-configuring networks. Looking farther ahead now is the time to prepare for densely integrated photonic components. The development of CAD and verification tools for PICs will have the nearest term payoff. Putting in place foundry models and mechanisms now is critical to make sure it is available in the long term.

There are basically five broad classes of network that are of interest today where optical networks play a role. These classes are:

- **Open public networks --** in particular, the Internet. The Internet is designed to maximize access and connectivity among parties connected to it. The Internet today relies heavily on optical fiber.
- **(Virtual) Private Networks (VPNs) --** Private networks are just that – networks which are not connected to the public networks. Private networks are typically created to protect the information they carry. Virtual private networks (VPNs) are private networks created by the use of encrypted channels layered on top of the public network. Whether physically isolated or a virtual overlay, private networks use much the same technology as the public network.
- **"Big Science" networks** -- While the trend in science has been to move resources onto the public networks, to maximize their availability and utility, there are some scientific applications that continue to find it useful to use private networks – often because the bandwidth needs are higher than the Internet can easily provide. Currently, this bandwidth is provided through optical fibers.
- **Sensor Nets --** In recent years, there has been a surge of interest in sensor networks. Sensors are measuring devices, often very small and with limited computing capability.

The initial idea was simply to network the sensors to ease retrieval of their data. However, as the field has matured, it has become clear that the ability to communicate enhances sensor capabilities (e.g. two adjacent sensors can compare their measurements for consistency). To date, almost all sensor networks research has assumed that communications is RF wireless. Recent work on fiber-optic based sensor nets in ocean environments illustrates the potential for cross-fertilization between these communities.

- **Wire-free networks --** Independent of sensor networks, the past decade has seen an explosion of interest in communications technologies that do not require a wire or cable. Freedom from wires is appealing both because of the reduced installation effort and because, in situations such as satellite networks, wiring is not feasible. It is widely believed that in some wireless environments, most notably space, free space optics is a very desirable, if not fully explored, interconnection technology. The bandwidth limitation of wireless networks also points to a more intimate connection with underlying fixed fiber infrastructures to enhance performance.

It seems unlikely that this broad classification of networking will change in the next five years and it provides us a context for the short-term research issues.

3.1 End to End Dynamic Networking

One vision of optical networking over the next five years is a network infrastructure that enables end-to-end dynamic (transparent) optical circuits that can be automatically set up in a matter seconds, rather than today's days or weeks provisioning time. These dynamic optical circuits provide transport to edge-connected electronic packet and circuit services. In order for this type of network to be compelling and make economic sense, there cannot be a large overhead on per wavelength (circuit) basis. Determining this cost is a complex computation and spans many aspects including capital costs, operation, and maintenance.

This vision is the one being implemented by the marketplace, as it is the most straightforward evolution from today's network and has the highest chance of interfacing and positively affecting the economics of broadband networks. To a large extent the basic components of this vision were invested in during the optical network boom of the late 1990s. However, there is still substantial work required to realize this vision and, for the moment, it carries higher risk or investment costs than vendors and domestic carriers are willing to spend.

The US still lags behind some major industrial countries (notably Japan) in dynamic circuit switched network infrastructure research and commercialization. In the US networks with ROADM technology are only beginning to be deployed nationally today. For a number of complex reasons, we have not moved nearly as far forward as we could have. At the top of the list of these reasons are combinations of complexity of software for management and network control as well as cost of optics due to lack of integration technologies and models akin to electronics.

Summarizing the situation, there is a default vision for optical networks in the marketplace that is not being pursued as vigorously as it might be. An open research issue is how to respond to this situation. This situation represents one opportunity to have an impact in the near to medium time frame.

We believe the NSF should focus research attention on those significant challenges which fall slightly outside industry scope – in particular, high risk work that sharply improves technology performance (thus driving industry costs down) and future-looking work that seeks to eliminate potential deployment/operational roadblocks (e.g., what problems might we hit in five years and how can we get rid of them before they become problems?).

There are some significant challenges that the research community can take on. The challenges span from device and physical layer research to network protocol and architecture research. The near term research challenges include but are not limited to:

(1) Technologies to optically monitor the signal quality and link and node states

(2) True network level dynamic bandwidth allocation

(3) Impart intelligence (for automation) to photonics devices and subsystems, through integration of photonics and electronics.

(4) All optical transport and transmission mesh networks that are self-configuring, self-managing, robust, and secured.

(5) Reduce the cost of optical amplifiers through new optical transmission and modulation techniques and impart a more digital nature of all-optical links and nodes through optical 3R regenerator technologies.

3.2 Moving from Rings to Meshes

The evolution of WDM transmission technologies has rapidly evolved to the point where all-optical networks are now practical on a network diameter of the order of several hundred kilometers - i.e. exceeding most metro areas in size, though not yet able to span long haul national or internationally in the optical domain. Similarly, there remain limits within the metro region where OEO techniques must still be employed to address wavelength blocking. New technologies (from a network perspective) such as optical SOAs may be able to push this limit over the next several years, and these devices will potentially find application for all optical wavelength translation (with appropriate levels of optical performance monitoring) within the metro space as well.

Further, all optical switching technologies - in particular MEMS technologies, have finally begun to be commercially available in field deployable systems. Other optical switching technologies are lurking on the horizon, but have not matured into robust product features capable of integration into high level network systems. Nevertheless, wavelength selective switches and reconfigurable OADMs have arrived and now offer a significant new network capability in terms of "spectrum" networking - the ability to allocate wavelengths that are framing and bandwidth agnostic.

Another critical step in commercial networks is to move from legacy ring networks to optically switched mesh networks. This change would enable an order of magnitude increase in capacity with an order of magnitude decrease in size and power.

Key to mesh networks are more powerful, multiway, switching elements. Although the nodes of order two are now largely optical, more complex nodes of order 3 and higher are typically electrically switched. However, optical switching technology has rapidly developed over the past decade, and the technology now exists to optically switch nodes of order three and higher.

From the network perspective, these three features of optical evolution (expanded unregenerated distances, optically transparent switching capabilities, and multiway optical switching) present serious challenges in the control plane. We need to see a better method for managing an optical network – what we call a *Control Plane for Dynamic Switched Optical Networks*.

Central to the control plane is an integrated package of tools (or mechanisms) to manage a mesh network so that it has the same fail-over/recovery times as a ring network, yet provides greater capacity and reliability, and can provide these services across provider boundaries. Challenges include wavelength routing in real-time, application-specific bandwidth allocation and management, and extending these services both deeper into the network and closer to the network edge.

3.3 Network Link Bandwidth

A perennial question is "how fast can we go?" Embedded in the question are issues of parallelism, media and coding. The clock rate has been continuously increasing ever since the first fiber optic systems at 45 Mbit/s were installed in 1978. Clock rates consistent with 10 Gbit/s are now widely deployed and 40 Gbit/s systems are just starting deployment after many years in the product cycle. Research on 160 Gbit/s transmission systems is an active and productive research area with both laboratory demonstrations and even several field trials in Europe. Innovation in techniques for pulse formation, modulation, multiplexing and demultiplexing, and clock recovery are an active research area. Electrical time division multiplexing (E-TDM) is the standard approach up to 40 Gbit/s and optical TDM (O-TDM) has dominated above that bit rate; however, this boundary continues to move upward.

High spectral efficiency modulation in the optical domain requires precise phase and amplitude control of the optical carrier. While today it is possible to demonstrate simple coherent optical modulation (e.g. duo or quaternary constellations), sophisticated modulation formats like that used in RF wireless systems (e.g. 64 QAM, etc.) are only possible when the phase and amplitude of the optical field can be precisely controlled. As discussed later in this document, we believe integration is one of the crucial steps in providing a communications technology with this level of carrier modulation control.

3.3.1 Parallelism

Much of our ability to transmit huge amounts of data using optical frequencies has come from parallelism – the ability to transmit concurrently at high bandwidths on many frequencies. In fiber, the challenge of parallelism has involved minimizing the size of side or guard bands, so that we can pack the maximum number of channels into fiber's narrow passbands. However, the ability to pack the fiber channel with large number of channels is fraught with challenges from signal impairments resulting from non-linear distortions in the optical fiber, to accurate alignment and stability of frequency selective elements in the data path. There are tradeoffs between the maximum power that can be transmitted in the fiber before distortions set in and minimum transmitted power before the signal-to-noise-ratio (SNR) degrades beyond recovery.

Wavelength division multiplexing (WDM) dominated the 1990s after erbium doped optical amplifiers (EDFAs) became commercially viable. Figure 1 shows the increase in capacity of WDM systems. Spectral efficiency of 1 bit/Hz with OOK is possible, and higher efficiencies have been demonstrated using multilevel coding. This area of research has been focused on point-to-point links and demonstrating the highest capacity over the longest distances in point to point networks with point-to-point fiber capacity in excess of 10 Tbps demonstrated.

There is general agreement that the optical communications field will continue to make improvements in parallelism (more channels per fiber) and individual channel for the foreseeable future. Most recently, NTT Japan demonstrated 1000 wavelength transmission over a single fiber. Unlike the early 1990s, this is not a research area in which we are woefully behind the demand curve and in desperate need of innovation to keep up. Furthermore, tech transfer from research to industry is working well in this area, so research innovations rapidly reach the marketplace.

3.3.2 Modulation and Transmission Research Challenges and Opportunities

There is a major research challenge that could transform the field of optical communications: finding a way to transmit with spectral efficiency orders of magnitude better than 1 bit per Hz. The current state of the art is approximately 0.8 bits per Hz and we have been stuck at that number for over a decade.

Why we are stuck on the spectral efficiency curve can be linked to our ability to control the amplitude and phase of the optical carrier to the precision necessary to allow a complex modulation and detection space. Photonic components have not reached the level of maturity required to provide the dramatic decrease in line width and phase noise seen in RF wireless components over the last 30 years. ***One of the opportunities looking forward is to find ways to make the optical carrier and modulation space agile and controllable built on a technology that can be interfaced with electronics in a manner that can be used to build real networks. This degree of control of the optical amplitude and phase space can be accelerated and enhanced by photonic integration.***

A second piece of the puzzle, one that goes hand in hand with new modulation capabilities, is the error free transmission of these signals over the fiber between source and destination. There are vast improvements to be realized in how to control and manage high capacity transmission over optical fiber in the presence of signal impairments, particularly over often unknown and varying fiber pathways. Just as there are vast improvements to be made in complex optical modulation schemes, there is unexplored territory in the transmission and all-optical regeneration of these modulation schemes. Understanding how these high spectral efficient signals will propagate error free, which modulation schemes are more robust to transmission impairments, what types of regenerators are required, and how to realize complex modulation regenerators in photonics without significantly driving up complexity are all major challenges with high payoff. There exist other mechanisms to increasing the capacity by increasing the number of modes beyond frequency and level. For example multi-mode fibers and free-space optical systems offer many orders of magnitude greater modes in which to communicate than single mode fiber. However, these additional degrees of freedom are very difficult to control in a communications environment. New research in how to exploit these additional degrees of freedom in a control manner is an important aspect to consider moving forward. ***A critical research opportunity exists in improving our understanding of how to transmit ultra-high spectral efficiency modulated data error free and the impact of fiber impairments, what technologies can be used to realize high-spectral efficiency all-optical regenerators and how these regenerators can be realized without significant increases in complexity as the channel count and bit-rate increases.***

3.4 Enabling Steps for Photonic Integration

Photonic integration is critical to evolving optical networking. Innovations in integration as well as making fabrication facilities available for more ubiquitous use of photonic circuit designers are critically important. This is particularly true in photonics because the capabilities as well as limitations of photonics are different than classic electronics and may require some differences in networking element architecture to leverage strengths and mitigate limitations. There are three key steps that need to be taken in the near term.

3.4.1 Design Tools for Photonic Integration

In order for integration to happen, design, simulation and verification tools for photonics that need to be developed, similar to what exists with electronics. Current EDA tools for PICs and ASPICs, are clearly a long way from the situation in electronics. Part of the issue is that the key building blocks for PICs, while having improved considerable over the last number of years, are still not fully mature and stable. In addition, there tend to be more different building blocks than in electronics. ***There's a short-term need to develop tools in support of photonic integration or long-term research will be stymied or delayed by lack of support resources.***

3.4.2 Production Testing for Photonic Integration

If we seek to move to producing complex *photonic integrated circuits* (PICS) in chipsets, we will need techniques to test the chips as they are being produced. Today's silicon production houses use extensive testing during production to weed out defective chips. As InP PICs become more complex, we will require more sophisticated automated test strategies and techniques.

3.4.3 Packaging

Photonic integrated circuits need to be packaged with fiber inputs and outputs, and be compatible with mounting on an electronic circuit board. Packages need to have some level of shock and environmental testing during the development stages to ensure the device can be used in a circuit card oriented system environment, however, there should be no guarantee that the device can be used in any or all environments other than a laboratory.

3.5 Physical Layer Scalability: All-Optical Digital Regeneration, Optical Signal Processing and Optical Performance Monitoring

A tremendous challenge to realizing scalable networks is all-optical regeneration and amplification, preferably at the chip level, to make optical networks behave more digital like. Within an optical device, some signal strength is lost as it crosses each piece of optical logic. After a few stages, the signal strength must be renewed. Currently that can only be done via an optical-electrical-optical device. If we are going to have chipsets that aggregate several optical devices into one chip, we will need optical regeneration inside the chip. The capability to do regeneration with reshaping only (2R) and reshaping with retiming (3R) is needed. New technologies that implement 2R and 3R multiwavelength regeneration similar to today's amplification only (1R) multiwavelength technologies will have very high impact.

A second problem to scaling optics in a network is non-digital signal processing to manage various aspects of the analog nature of the signal, like filtering and switching. In addition to performing non-digital signal processing functions, the quality of the signal in the analog and digital domains must be accessed using optical performance monitoring techniques. These techniques to access the "state" and "health" of various aspects of the network are critical to building a scalable, manageable network. New optical performance monitoring techniques, their low cost integration at the chip level (so they can be utilized pervasively) and the coupling of these functions to network management and control plane software remains a vital part and critical challenge moving forward.

3.6 Quantum Networks

Quantum networks represent a very different research frontier, in many ways pulling in directions orthogonal to the other research thrusts. There are actually two types of quantum networks: quantum key distribution networks and quantum data networks. The two networks are very different, both in concept and their maturity.

3.6.1 Quantum Key Distribution Networks

Quantum key distribution networks are designed to securely distribute cryptographic keys. The technology has been demonstrated for single links for the past few years, and in the past year, we have started to see working networks.

The basic idea behind quantum key distribution networks is the following. A photon can be thought of as being able to spin on two axes have two polarizations– horizontal and vertical. Suppose you have the capability to encode a bit in a single photon using either of these two axes. Now send the encoded photon to someone you wish to communicate with, without telling them which axis you've encoded the bit on. The receiver randomly chooses an axis and reads the value. Then you tell them which axis you sent on. If the receiver read on the same axis that you sent, then you've successfully communicated a bit.

While this method of transmitting a bit (with a 50% loss rate!) sounds convoluted, two additional observations suddenly make it very powerful. First, suppose that there's a third party between you and the recipient and the third party wishes to see the value of the bit. The third party must capture the photon, read the photon and then generate a new bit encoding to replace the value read. But, because the third party does not know which spin polarization to read, there's a 50% chance that the third party will read the wrong spin and generate garbage in the regenerated value. So, effectively, an attempt to intercept communications will increase the number of photons incorrectly read by the receiver. If the receiver and sender periodically compare notes about which bits got through correctly, the sender and receiver can detect the third party. In summary, the ability to encode in a single bit combined with the physical properties of the photon give us a communications channel that cannot be covertly tapped.

Creating such a quantum key distribution network involves tremendous effort. One needs a way to reliably generate single photons with the desired spin, reliable single photon detectors and a way to combine these single photon transmitters and receivers into a network. And there the problems get truly exciting. For the same reasons that a third party cannot tap photons, we cannot include any logic between the sender and receiver in which the photon is effectively read. Therefore, in order to transmit and switch individual photons, we must use a very low loss switching techniques.

Architecturally, there appear to be two take-away points about quantum key distribution networks. ***New research in ways to distribute large amounts of secure keying material in real***

time using quantum key distribution networks is required. Understanding how the requirements of quantum key distribution impacts how we implement fiber optic communications systems is another critical area of research.

3.6.2 Quantum Data Networks

Quantum data networks are a higher risk area than quantum key distribution networks. Quantum computers operate on quantum data and are capable of performing highly parallel computations in parallel using compound bits called *qubits*. Qubits can be thought of as having multiple values at the same time, stored in quantum states. ***If past history is any guide, once significant progress is made in quantum computing, there will be a natural progression to network these computers***. This means transmitting qubits. Important research challenges will emerge due to the nature of qubits. For example transmission requirements, as with quantum key distribution networks, may be incompatible with standard optical transmission technology.

An open question is whether we can convert the qubits from their form internally in a quantum computer into a form that works well over conventional networks (an idea dubbed a "QCQ" conversion – for quantum-conventional-quantum). If not, then we are faced with the same issues as in quantum key distribution networks – namely how to design a fiber optic infrastructure to meet multiple types of use.

4 Long Term (6-15 year) Opportunities

As we look farther forward than 5-years, we see the prospect of revolutionizing optical communication. In this transformed world, optical communication is a fundamental interconnection technology at the edge of networks, rather than simply in the middle – and the edge of the network is moved inside the computer – perhaps even so far as direct connection to the central processing unit (CPU) or peripheral. This revolution would come as the result of an enabling technology combined with a push to apply that technology to several challenges.

The enabling technology is *photonic integrated circuits* (PICs). The field is moving rapidly to putting large amounts of photonic logic on an integrated circuit (which may be silicon or may be some other substrate material). So we can envision optical devices of increasing complexity in ever smaller and more power-efficient packaging.

We would seek to use PICs to solve the following key challenges:

1. *Electronic Field Programmable PICs (EFP-PIC).* The goal here is twofold: (i) To enable researchers to specify what *optical* functions the PIC needs to perform and (ii) to make that function usable or programmable from the *electronic* control plane and signaling layers. In principle, the electronic field programmable PIC should have all of the advantages and benefits that FPGAs have offered to the electronic designer, but with photonic functionality. Furthermore, if one reprograms the electronic FPGA, the same PIC could be reconfigured to interface with different optical communications networks (e.g. different topology, protocols and transmission rules). ***The core idea is to transform optics from a technology with static components (fixed lasers, fixed signaling) to a dynamic technology that can be controlled from the electronics in a manner very similar the way electronic control of electronic systems is handled today.***

2. *Optical Switching*. Communications data generally comes in two forms – very large (a video or a large database file) or very small (a packet, a component of a web page, a bus transfer). One goal is to make available optical devices that switch 100 Gbps optical channels with rapid switching times (under 1ns) and that is more amenable to switching small data granularity (at the sub-wavelength level). A related observation is that the areas in which the large/small boundary appears to be changing. There are preliminary studies that suggest the center of the network may be a region where buffer requirements are low (due to the law of large numbers), reducing the need for large number of optical buffers, and other approaches that indicate that aggregating disparate packets into larger bursts may give acceptable performance. There is also the prospect for optical switches to move closer to the network edge, and indeed, into edge devices.

4.1 Innovations Enabled

A revolution in optical communications will enable innovations in many forms but, so far, they seem to fall into two broad categories: moving optics inside the computer (breaking down the crisp dichotomy of electrical computing and optical communications) and making optical communications (over any distance) more flexible and dynamic.

4.1.1 Optical Connections on the Circuit Board

The ability to multiplex very large quantities of data on a chip and transmit this data from chip to chip is an area of intense interest to both the research and commercial communities. The commercial sector is making huge strides in this area using standard modulation techniques and existing device technology integrated onto new platforms, some CMOS compatible. However, this connection technology is increasingly a challenge in circuit board design and there is tremendous potential benefit to a forward-looking approach based on optics.

A newer challenge is to use optics on integrated circuit boards, as the preferred technology to interconnect chips or chipsets. The challenges here are to pack as much optical transmitter and receiver multiplexing capacity on chip as possible. Since the transmission distance between chips is very small (compared to a network), distortion impairments are not as much an issue. Cost, footprint and power dissipation however are critical issues. New spectrally efficient coding techniques can also have a high impact in this area, as the ability to mover more information onto and off of the chip using parallel techniques becomes limited by the connection of the fiber to the chip and chip area**.**

PICs are clearly what enable this vision. And they may be all that is required. While it is easy to assume that fast switching is also required – the rich bandwidth available in a small area may obviate the need to switch. (E.g. rather than sharing a bus, there may be enough capacity for every component on the board to have a permanent optical channel to every other component it needs to communicate with).

4.1.2 Optical Backplanes

It has been apparent for some time that optical interconnects eventually will be required in high performance computer backplanes. The challenge has been getting optics ready to take on the challenge.

Today's highest capacity machines (e.g. routers) utilize electrical backplanes to allow very high cross-sectional bandwidth to be spread within a shelf and rack. However, as the system capacity increases and power dissipation becomes a limit, these systems must be spread out over many racks and distributed optical backplanes must be employed. While this solution of interconnecting many processors, buffers, IO cards and switches allows systems to scale to very high capacity and throughput, the cost comes at the expense of converting data between electronic and optical form many times as data moves from the rack to the inter-rack interconnect, yielding a large power inefficiency (especially as the bit-rates continue to increase) and forcing the system to be spread out even further over multiple equipment racks.

That people go to the effort to build the high-speed electronic backplane within a rack points to the economic and design limitations of optical backplane technology. Most optical backplane technology is static (or quasi-static). We still don't have low-cost, scalable optical backplanes that can alter their connectivity (e.g., connect and disconnect devices) in a timeframe consistent with the short transactions that characterize backplanes. The present result is that, for very high bandwidth systems, we build rather clunky devices that use electronic backplanes, interconnected with point-to-point optical fiber, to build a sort of distributed backplane. Here again, PICs are the enabler.

4.1.3 Breaking Down the Network/Computer Boundary

If both the circuit board and the backplane are optical, an opportunity exists to push forward the notion of treating networking and computing as fundamentally one field. From a pragmatic perspective we've struggled to break down boundaries between computers and the networks that serve them, yet remain a far distance from realizing this vision. ***A key challenge is to investigate the potential to bring the all-optical network into the backplane, the circuit boards, and edges of the chip. If this is possible and desirable, then the boundaries really will be gone – because they are physically (not just intellectually) removed***.

Getting to this point requires advancements in almost every area discussed in this document. If we get there, we will have to examine how to re-introduce boundaries (we don't want someone else's computer to transparently connect to your computer's memory). But the intellectual freedom of choosing where to place boundaries (rather than having technology force the boundary points) is an opportunity for great research achievements.

4.1.4 Rethinking the Router

Over the past quarter century, demand for router performance has grown at a rate slightly higher than the rate of improvement provided by Moore's Law. Thus, as each new generation of router has been produced, its designers have struggled to squeeze out some extra performance beyond what the latest (Moore's Law improved) chipsets provided. Over time, this has led to the creation of ever more complex routers. ***We're now at the point where power dissipation is a key issue in router design and high-end routers often occupy multiple racks.***

One way to look at the power problem is to observe that routers pass both the payload (packet processing) and the header (lookup processing) through electronics. Therefore electronic bit-level switching energy must be dissipated to both forward packet payloads and process lookup information. The higher the payload bit-rate is, the more energy is dissipated by each transistor in the payload-forwarding path. The new switching energy occurs at the packet edges plus a constant bias energy to bias the optical switching circuitry.

In order to address the power and footprint problems we need a better understanding of how the optical domain can save power when used in conjunction with electronics. PICs that do not require cooling will be an essential aspect moving forward as the power consumed by cooling technology (e.g. thermo electric coolers) can often dominate the power dissipated by the PIC itself. For example an optical chip that consumes 1W power today may require an additional 3-5W to cool it. Therefore "cooler-less" PIC technology is a critical component of any research program moving forward.

Achieving either solution within the next decade would be an exciting result because both solutions require several hard problems must be overcome, including:

- *Fitting packet switching/routing logic into a PIC.* Both the all-optical and the hybrid solution require optical routing logic. The all-optical approach requires us to fit all the typical routing logic (route lookups, checksums, packet header checks, firewall filters and multiple priority queuing schemes) into a PIC. The hybrid approach is less demanding but still requires to ability to determine how much of the front of a packet must be converted into electronic bits, and to seamlessly split and recombine electronic and optical portions of a packet.
- *Chip level optical buffering.* While recent work strongly suggests we need far (orders of magnitude) less buffering in core routers than was previously thought, we will still need several packets' worth of buffering in any router interface. Creating optical buffering that can be placed on a chip is challenging and could require new physics to be employed and integrated.
- *Correctly balancing electronics and optics.* While this problem may appear to only be of relevance to a hybrid approach, it actually applies to both. Even in an all-optical router, it is likely that much of control system managing the system will be electronic. And it is very easy to design a system where the size (and heat dissipation) is still dominated by electronics. We are likely to have to go through a couple of research design iterations before we get a system that properly balances electronic and optical components. This balancing should be done to optimize a variety of metrics including performance, footprint and power dissipation. Realizing cooler-less technologies (PIC and Hybrid) are an important aspect of this balance.
- *Alternative optical connection models and switching paradigms.* While the electronic router may remain a packet switch, it is not clear if optical router technology should mirror this environment or add to it. For examples, optical switching technology can be utilized for fast or virtual circuit switching, burst-switching, etc. These alternate connection models need to be explored in more detail as well as the role optical router technology plays in cooperation with electronic router technology. In this respect the very definition of what an optical router is remains an open issue in itself.

4.1.5 Agile Optical Networks

Unlike today's optical transport networks that are relatively static (optical pipes are setup and changed more for network functions than rather for data routing requirements), agile optical networks would allow bandwidth in the wavelength and time domain to be accessed on demand without restrictions to the wavelength granularity. Users or nodes could access that portion of the bandwidth they needed when it was needed.

This vision is already causing a revolution in the RF wireless community as broad-spectrum and tunable transceivers are being combined with digital signal processors to create software-defined radios that adapt their behavior as needed.

While the programmable network solution for optics is likely to be different than its electronic counterpart, in large part due to differences in what physics permits, ***making the optical spectrum a programmable media will invigorate optical device and network research and make optics an accessible technology to the broader network researching community***.

Programmability will also have great practical benefits. Innovations in coding and modulation could be rolled out into the field without having to upgrade equipment (must as new code in flash is used to upgrade modems). Equipment could more easily auto-adjust, easing installation challenges. Programmability is also vital if we're serious about combining computing and optics in CMOS. There are two goals that lead to combine computing logic with optical logic on one chip: the first is simply to interconnect chips using optics, the second is to create a more flexible optical device. And if we want to achieve the second goal, the computing power needs to be coupled to an optical device that is programmable. One can also view the creation of programmable optical devices as a way to re-examine the underlying physics of optical communications – to take advantage of the fact that optical media is fundamentally analog.

4.2 Photonic Integration and Embedded Intelligence

Photonic integration is essential to realizing any of the innovations mentioned in Section 4.1. This section looks at what needs to be done to make photonic integration a reality (beyond the critical need to develop tools noted in Section 3.4).

4.2.1 Benefits of Photonic Integration

Photonic devices have multiple figures of merit. Examples include reconfiguration speed, loss, polarization dependence, footprint, power dissipation, crosstalk and optical bandwidth. One of the distinguishing differences between photonic devices and their electronic counterparts is the power dissipation relative to the number of wavelengths the device handles and the bit-rate per wavelength. Many photonic devices require a holding or bias power, but do not dissipate power on every bit of data that passes through, as is the case with electronics. Balancing these benefits, photonic devices do not have the embedded level of intelligence of electronics nor can they be integrated at the density of electronics.

The challenges that exist today are to realize photonic devices that either complement or replace electronics. This change is possible if we innovate new technologies that

- Make the interface between optics (communication) and silicon (computing) as efficient and inexpensive as possible.
- Allows use of the best technology for the best job. For example, CMOS for computing/processing and optics for all transmission and maybe switching.

The question is what integration platforms will be used to achieve these goals. Today we are still not sure of the answer, but there are compelling contenders including

- InP
- Silicon
- Si/InP
- Hybrid chipsets

4.2.2 Challenges in Photonic Integration

There are a number of challenging issues in photonic integration and no doubt more challenging issues will become apparent as work progresses.

4.2.2.1 The Challenge of CMOS

To date, we are unable to produce a complete active optical device (a laser) in standard CMOS. We must manufacture our optical chipsets using non-standard materials such as silica and use them as either standalone components, or layered onto a CMOS chip. Today CMOS compatible photonics must utilize InP active technology (for sources and amplification) in hybrid chip configurations or using wafer fused technology that merges silicon and InP materials. There is work today that needs to continue to push the envelope of amplifying Si photonics that is compatible with CMOS electronics.

4.2.2.2 The Challenge of InP

Photonic circuits that switch and amplify and provide on-board light sources are fabricated in indium phosphide technology. Many of these functions are not available in other integrated platforms. The issues that must be addressed in this technology include moving to large scale integration, fabrication using larger wafers than today's 2 or 4 inch substrates, increasing device yield, on-chip testing methodologies, and for active waveguide technology, decreasing waveguide loss by more than a factor of 10 over that doable today.

4.2.2.3 The Need for All-Optical Regeneration

The issue of all-optical regeneration was noted in section 3.5 but bears repeating. In order to pass digital data through many stages of PICs, signals need to be reshaped and retimed. All optical techniques that can be integrated on-chip are essential. Equally important is regeneration for transmission that can support 40Gbps and above over distances of interest (depending on the application). Sending high-speed data over appreciable spans with all-optical nodes is critical to building real scalable networks, and regeneration is a key pin in this scenario.

5 Recommendations

While the visions for the future of optical communications will invariably evolve as research evolves, we believe that a recommendation for the broad picture can be made. At the same time, one of the messages from the workshops is that the optical communications community is ready and eager to revisit assumptions behind some of today's technology. There's an interest in re-examining the basic physics of optics; to seek out optical capabilities not yet exploited. We sit at a very fertile moment in optical communications research and our challenge is to take advantage of the moment, and seek to make the research leap forward.

5.1 Recommendations for the NSF

We make the following recommendations based on the outcome of this study and the two workshops.

5.1.1 Foundations

a. *Build the foundation for photonic integration.* This includes developing a comprehensive set of optical modeling tools for enabling the transition to widespread use of robust optical foundries, development of a silicon CMOS compatible photonics integration technology, and development of more complex, higher yield indium phosphide and silicon technology.

b. *Expand the fiber capacity* of single mode fiber and new research on multi-mode, free space and plastic fiber is appropriate and may pay dividends. New techniques to send data more efficiently over fiber, including more efficient coding and free space and multimode fiber transmission. How do we drive the number of bits per hertz substantially higher?

c. *Re-examine and expand our understanding of what optics can do in tomorrow's optical networking environment*. Research that increases transparency of the network media is important to build ever more reliable and richly connected optical networks. What does transparency mean when we in a quantum communications environment? Rethinking media and rethinking transparency are chances to better understand and perhaps a way to get insight into how optics needs to be programmed.

d. *Optical modulation and regeneration*. New techniques to send bits of data more efficiently over the fiber and allow all optical transmission and networking to be more like digital electronics systems will be a disruptive advance in optical networking and will allow researchers to re-think how optical networks can be utilized in the broader networking field.

5.1.2 Engineering of Devices

a. *PIC CAD Tools*: The development of new PIC CAD and verification tools is critical to enable foundries in the future and open this technology to the broader network community.

b. *Programmable Photonics*: Integration at least at the board level, and eventually in one package, of programmable electronics (e.g. FPGAs) with photonic chips and development of standardized interfaces so programmers and systems designers can utilize photonics much in the same manner as today's programmable electronics.

c. *Cost Reduction:* Photonic integration is critical to expanding the complexity of optical networks and interfaces while reducing their cost. One important direction is increasing the InP wafer size from today's two inch substrates to four and six inch substrates along with increasing device yield and reducing waveguide loss.

d. *CMOS Compatible Photonics:* An important direction is to develop a CMOS compatible photonic integrated circuit processing capability and solving the fundamental problem of building lasers on silicon, an indirect bandgap material.

5.1.3 Networking Systems and Architectures

a. Re-examine and expand our understanding of what optics can do in tomorrow's optical networking environment. For example reducing the power requirements of routers, computers and switches.

b. Architectures that build on transparency and ability to rapid dynamically reconfigure the network. Enabling higher capacity networks that are reconfigurable, more flexible and have much higher capacity at much lower cost. This involves moving from ring to mesh networks, from fixed wavelength allocations to tunable transmitters and receivers, from networks without optical buffering to one with intelligent control planes and sufficient optical buffering.

c. One category of opportunity is moving optics inside the computer. This requires making optical connections on the circuit board, which requires photonic integration, particularly phonic integration onto a silicon VLSI platform. High performance computer backplanes require optical interconnects, which again depends on low cost photonic integration, particularly with CMOS. It also requires low cost optical switching.

d. New control plane technology and algorithms that allow rapidly dynamically reconfigurable optical network infrastructures to be realized.

e. Interfacing optical technology with other network technologies like wireless and mobile.

f. Rethink our assumptions about optical communications and the role it plays in the broader area of networking (Clean-Slate Approach).

g. Create new programs designed to increase the interaction between the applications, network architecture and physical layer research communities and designed to decrease the language and scientific barriers that exist today between these communities.

5.1.4 Recommendations on design or structuring of funding programs at NSF to help realize the research agendas.

The structuring of programs to implement the recommendations of this report is a critical step in realizing this vision. Since optics is not as mature a technology as electronics it is important to design a program that both progresses the maturity of optical technology towards that of electronics and at the same time incorporates state of the art optics technology into experimental network infrastructures. We recommend that the NSF structure funding programs along the following lines.

Re-Focused Research Programs

It is recommended that the NSF start a cluster of re-focused research programs that are geared towards addressing the fundamental issues outlined in this report as well as advances the state-of-the-art in engineered devices is recommended. These refocused research programs should be able to utilize and in time contribute to experimental facilities described below. We believe that this unified approach will lead towards re-integration of the optics and networking communities as well as lead to major innovations and advances in Internet network technology and applications. Examples of re-focused research programs include but are not limited to:

- Ultra efficient high-bandwidth optical communications and networking.
- Highly integrated photonic network functions and network elements.
- Programmable optics – Integration of photonics and electronics.
- Rapid dynamically reconfigurable optical networks and control plane technology.
- Quantum optical communications technology, systems and networks.
- Cross-layer design programs designed to increase the research interaction between applications, network architecture and physical layer research communities.

Experimental Facilities and Infrastructure

In order to apply optics as a useful networking technology and integrate it with other network technologies, we recommend programs that fund more experimental and infrastructure facilities. These facilities are needed to provide the critical bridge between research in optical technologies and research in networking.

- Funding new network infrastructures that allow deployment of optical network (transmission and node) technology in a manner that allows network researchers to use optics as one of the tools to investigate the scientific underpinnings of new, untested networks and applications. These experimental facilities should enable networking researchers to utilize, through control plane and network control mechanisms, to study network issues that cannot be studied on today's Internet.
- Funding a new photonics foundry that makes optics a more usable, widely accessible technology to a broader class of network architects and researchers. The foundry should follow the success of MOSIS and bring to bear the vast photonics device resources in the US today and make these resources available to optical device and network researchers.

Periodically, NSF should fund (via workshops or studies) to assess progress of these programs. We hope and expect that at some point in the next several years it will become clear we have reached a maturing point for photonic integration, and at that point should devote most of our energies to exploiting photonic integration to revolutionize optical communications.

5.2 If NSF were to follow these recommendations, how this would contribute towards realizing the potential of disruptive technologies?

The major disruptive technology is the photonic integrated circuit (PIC) and it broad use by networking research as a "usable" technology. The two-pronged research path is designed first, and foremost, to cause PICs to appear as soon as possible in real network experiments and demonstrations, and second, to use the time spent developing PIC technology to more completely explore how fiber optics behave and can be used, in the expectation that results can then be used to develop even more capable PICs.

5.3 Recommendations for the research community

If past history is any guide, the development of dense PICs (PICs with lots of optical logic on them) is likely to produce a paroxysm of innovation: a period of time when new ideas and new capabilities come fast and furious and there will be little time for reflection in the rush to develop new chips.

So the time for reflection and for creative research that expands our understanding of optics is now! How do we get more bits per hertz? How do we make networks transparent to new modulation formats and transmission technologies? What's the best way to program an optical DSP in a PIC? It is clear from our workshops that many optical researchers are intrigued by these sorts of questions – now is the time to pursue them!

5.4 If the community were to follow these recommendations, how this would contribute towards realizing the potential of disruptive technologies?

If, as we believe, the arrival of PICs means the start of a period where there's a rush to realize existing ideas in PICs, then spending time now to mature ideas is an investment in the set of ideas available when PICs become real. In other words, some thought now will lead to greater and more disruptive innovations in the future!

Appendix I: Attendees of Workshops

The first workshop was held in Santa Barbara from February 2-3, 2005 and was attended by:

Rod Alferness (Lucent)
Dan Blumenthal (UCSB)
John Bowers (UCSB)
Chip Elliott (BBN)
David Farber (CMU)
Nick McKeown (Stanford)
David Miller (Stanford)
Mario Pannicia (Intel)
Craig Partridge (BBN)
Guru Parulkar (NSF)
Adel Saleh (DARPA)
Alan Willner (USC)
John Wroclawski (MIT)

The second workshop was held April 12-13, 2005 in Santa Barbara and was attended by:

Bob Aiken (Cisco)
Ender Ayanoglu (UC Irvine)
Neal Bambha (ARL)
Paul Barford (Univ. Wisc.)
Keren Bergman (Columbia)
Dan Blumenthal (UCSB)
Javad Boroumand (Cisco)
John Bowers (UCSB)
Dan Dapkus (USC)
Roopesh Doshi (UCSB)
Marcus Duelk (Lucent)
Chip Elliott (BBN)
Shahab Etemad (Telcordia)
Darleen Fisher (NSF)
Joe Ford (UCSB)
Nick Frigo (AT&T)
Randy Giles (Lucent)
Vladimir Grigoryan (Northwestern)
Janet Jackel (Telcordia)
Olivier Jerphagnon (Calient)
Ivan Kaminow (Berkeley)
Gig Karmous-Edwards (MCNC)
Haim Kobrinski (Telcordia)
Prakash Koonath (UCLA)
Prem Kumar (Northwestern)
Stephen Liu (Verizon)
Steven Low (CalTech)
Debasis Mitra (Bell Labs)
Biswanath Mukherjee (UC Davis)
Radha Nagarajan (Infinera)
Loukas Paraschis (Cisco)
Craig Partridge (BBN)
Guru Parulkar (NSF)
Chunming Qiao (SUNY Buffalo)
Ramesh Rajaduray (UCSB)
Steve Ralph (Georgia Tech)
Dave Reeses (CENIC)
Adel Saleh (DARPA)
Jerry Sobieski (UMD)
Dan Stevenson (MCNC)
Dmitrios Stiliadis (Bell Labs)
Xun Su (CalTech)
Michael Tan (Agilent)
Tim Vang (Archcom Technology)
Malathi Veeraraghavan (UVA)
Allan Willner (USC)
John Wroclawski (MIT)

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