NSF Workshop
The Future Revolution in Optical Communications and Networking
Dec. 4th and 5th
Arlington, VA

Final Report Overview

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I. Introduction

Optical communications and networking has enjoyed almost unprecedented growth and success in the commercial sector in recent years, and still the high inherent bandwidth of optical fibers is just beginning to be exploited. However, despite the impressive growth projected for this field, industrial research is taking on an increasingly short-term focus, so that the long-term, high-risk research that is necessary to sustain the growth in information transfer capacity is not being aggressively pursued. We are now at a cross-roads in which short-term goals are dominating long-term investment, and this approach will eventually result in severe bottlenecks as society's demand for bandwidth continues to grow exponentially. Growth has been so strong that this industry is now facing two critical challenges: (i) ensuring the continuation of high-risk basic research required for the industry to sustain its rapid progress, and (ii) the training and hiring of qualified optical engineers from a depleted work-force. The National Science Foundation (NSF) is in a unique position to provide critical guidance and resources to help solve these problems.

The NSF has both an opportunity and responsibility to play a critical role in helping society cope with the growth of this industry, as well as in helping to stimulated the long-term inter-disciplinary research that is vital for this rapidly growing industry. In order to facilitate the goal of prompting revolutionary technical progress, the NSF sponsored a Workshop on high-capacity optical communications and networking on Dec. 4th and 5th, 2000, in Arlington, VA.

This Workshop highlighted research issues and key roles that the NSF can effectively support. The format of the Workshop included: (i) distinguished speakers that represented directions outside traditional research areas that can help complement today's optical communications work, (ii) discussion break-out sessions among the participants that identified high-risk research avenues that are critical to sustain the long-term growth of optical communications and that are not being pursued by industry. The approximately 85 participants in the Workshop included leading figures from academia, industry, and government agencies. These individuals were chosen to represent many different disciplines that could contribute to useful and multi-disciplinary recommendations to NSF.

A Steering Committee for the Workshop consisted of Neal Bergano (Tycom), Connie Chang-Hasnain (Berkeley), Mario Dagenais (Univ. of Maryland), Peter Herczfeld (Drexel Univ.), Leon McCaughan (Univ. of Wisconsin), David A.B. Miller (Stanford), Galen Sasaki (Univ. of Hawaii), and myself.

II. Program Highlights

Some of the materials, device, systems, and networking topical challenges that will be addressed by the Workshop include:

1. high-speed all-optical packet-switched networks and their enabling technologies
2. the seamless hybridization and integration of microwave wireless signals with the optical backbone
3. the next-generation of optoelectronic materials and devices that will fuel future capacity and functionality revolutions, such as photonic crystals, nonlinear processors, packaging, and integration
4. the identification of future shifts in optical communications technology beyond EDFAs and WDM
5. technologies that will help achieve greater than 50-Tbit/s optical fiber system capacities,
6. a pervasive smart optical environment
7. tradeoffs to achieve optimal network architectures for ultra-wideband and heterogeneous traffic
8. powerful coding and information theory to identify fundamental limitations and achieve better spectral efficiency
9. optics and electronics for >40-Gbit/s/channel systems
10. fundamental advances to achieve >300-nm-wide wavelength ranges
11. effective roles for the NSF in fostering a viable optical engineering work-force.

The 15 invited presentations were 20 minutes in length, with additional time for questions following. Each speaker addressed technologies that should reach the market place not within five years, but with a 5-15 year time horizon.

The following is a list of the presenters and titles:

• A Revolutionary Technology Roadmap Beyond Today's OE Industry	Peter Kaiser
• Technologies that Industry Would Like but Don't See on the Horizon	Bruce Nyman
• The Merging of the Wireless and Fiber Worlds	Dalma Novak
• The Future of Higher Nonlinearity	George Stegeman
• Photonic Crystals for Generation-After-Next Lightwave Systems	Axel Scherer
• The Merging of Optics and Electronics in Functional Devices	David Miller
• Optical Networking Research for the Next Generation Internet	Mari Maeda
• The Complementary Role of the NSF and Venture Capitalists	David Mueller
• Key Limiting Challenges for >25-Tbit/s Optical Fiber Systems	Andy Chraplyvy
• The Ultimate Capacity Limits of Optical Fiber Communications	Jan Conradi
• Interpretation of the Shannon Capacity Limits for Optical Comm.	Stewart Personick
• The Future Growth of Electronic Switching	Mark Horowitz
• What Will (Optical) Networks Look Like in 20 Years?	Ray McFarland
• What Functions Should be Performed Optically in Future Networks?	Dan Stevenson
• Optical Border Gateway Protocol	Bill St.-Arnaud

Shorter presentations were volunteered and presented by the following individuals: Joe Bannister, David Brady, Thomas DeFanti, Peter Delfyett, Rhonda Franklin-Drayton, Chi Lee, Linden Mercer, Jean Toulouse, and Ben Yoo.

The participants were divided amongst the four break-out sessions such that each group was composed of a multi-disciplinary group. The four topics and their Chairs were:

1. What Optoelectronic Devices Will be Needed in 10 Yrs? (L. McCaughan & C. Chang-Hasnain)
2. What New Techniques Will be Needed to Reach 50-Tbit/s Systems? (G. Carter & J. Conradi)
3. Will Future Networks Be Structured Differently than Today's Nets? (R. Cruz & G. Sasaki)
4. How Can the NSF Help Solve the Workforce Dilemma? (D. Brady & P. Delfyett)

The Chairs were responsible for keeping the discussion focused and for providing a report to the NSF on their group's recommendations.

Additionally, a working dinner with a lively group discussion occurred on the evening of Dec. 4th.

III. Recommendations

I will summarize some of the participants recommendations. A more detailed recording of their views can be found in the individual reports of the breakout sessions. (Note that, although the recommendations may not neatly fall into a single category. I have tried to place each recommendation in a suitable location.)

a. Overarching Funding Themes

- True revolutionary progress will require combining the talents of a multi-disciplinary group of researchers who are focused on a single problem.
- Both individual grants and team grants should be funded. Teams could be in the 3-5 person range. Ultimately, an entire NSF Engineering Research Center should be devoted to this area. This will be an ideal vehicle for making a major impact in this intrinsically interdisciplinary field.
- Smaller grants should be given to stimulate the development of truly novel ideas. More fully-formed ideas could be funded later with conventional-sized grants.
- Revolutionary progress should be defined loosely as enabling new functionalities, new paradigms, >4 times performance enhancement, or a >10 times reduction in cost.
- Stable and committed funding is required.

b. Materials and Devices

- New components are still using the same basic materials as building blocks, with all their well-known limitations. Fundamental chemistry and materials science must be brought to bear that will enable a whole new class of devices and system functionality.
- Novel fibers are now produced that can solve serious high-speed systems challenges. However, these solutions typically modify the fiber geometry. Accelerated basic glass and chemical research is needed to produce far more sweeping changes in over-coming limitations in systems.
- The power of optical connections and the power of electronic processing have yet to be "married" effectively. Enhanced performance and functionality, as well as significant cost reduction, have yet to be realized. After 20 years of work, true revolutionary work in hybrid optical and electronic integration and optimization must be performed.
- Some basic reasons exist as to the reason multi-wavelength networks are limited to $<<1000$ wavelengths. The most basic of them all is that no laser source exists that can provide such performance. Future multi-wavelength networks must have such a device in order to thrive.
- Optical switching is the next vista in industry, and yet no technology exists on the horizon for fast ns switching in a packet-switched network. Researchers must provide one using, perhaps, new materials.
- Low-cost and high-yield packaging and manufacturing remain a vexing problem throughout the optics industry. Moreover, long-term reliability remains elusive. Truly revolutionary solutions must be found for this industry to thrive in the long term.

c. Systems

- Optics has lagged far behind other technologies, such as wireless, in effectively utilizing the available spectrum. Present optical systems are well below 1 bits/Hz. Based on fundamental Shannon capacity arguments, novel coding and optical techniques will be needed to push the spectral efficiency well beyond the 1 bit/Hz range.
- Much industrial work exists at 10 Gbit/sec/channel systems, with 40 Gbit/sec/channel systems coming on line within the next 2-3 years. However, present industry is quite baffled by the question of whether ≥ 160 Gbit/sec/channel systems will be feasible. **The NSF must make sure that the proper research exists.**
- Innovative "smarts" in the guise of optical signal processing will be needed to provide new functionality and enhanced system capacity beyond the simple metric of "faster and longer" in optical systems.
- The projected growth in wireless traffic and optical fiber traffic is exponential, and capacity to meet this demand is also growing at a healthy rate. However, if this scenario continues, a severe bottleneck will occur at the interface where wireless traffic must propagate over the fiber backbone. The seamless interoperability of wireless and optical networks, including unique hardware, data formats, and protocols, must be funded. Such work is quite speculative but has a high future payoff.

d. Networks

- Optics provides high bandwidth, but the costs are still much too high. Low cost broadband access needs multidisciplinary research in order to make a critical difference in our society.
- Data rates have climbed to such high levels that the fundamental network designs of the core and periphery identities must be re-examined. New paradigms must be developed such that throughput and efficiency of the network can keep pace with the ultrafast optical components and large-volume bursty networks being invented.
- With high-speed data propagating in a futuristic optical packet-switching network, bufferless or small-holding-time algorithms and technologies must be created.
- Optics is clearly important in the network core. However, the potential advantages of using optics at the periphery remains a key question that must be researched.

e. Workforce

- The NSF should take an active long-term role in educating a new and larger generation of optical engineers**.** This should target all levels of education and training, including: K-through-12, B.S., M.S., Ph.D., and professional skills.
- The NSF should foster and disseminate new optical curricula that include laboratory experimentation and multimedia education modules.
- The NSF should fund an Engineering Research Center in this field, thereby building a large and uniquely-talented pool of university students who will deepen the workforce.