PHOTONIC SWITCHING



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Abstract

Photonic switching is a rapidly evolving technology that offers both faster speeds today and takes a giant step forward toward the creation of All Optical Networks (AON). While the present day environment may be described as a combination of optical components coupled with conversions to electronic components where necessary substantial research progress is being made toward widespread reductions and possible elimination of Optical-Electrical-Optical (O-E-O) conversions at some point in the future. These new developments may provide just-in-time engineering solutions to the rapid increases in data networking traffic associated with the Internet. This report examines the present day state of photonic switching with the caveat that the area is rich in experimental scientific research that may yield substantial changes within the next decade and beyond. If traffic projection requirements are accurate, profound changes in the core infrastructure that supports National Security/Emergency Preparedness (NS/EP) operations are likely. This report examines existing and emerging photonic switching network technologies, identifies current issues associated with deployment, and discusses their applicability to NS/EP environments.

Table of Contents

1	Intro	Introduction		
	1.1 1.2	Why is Photonic Switching Needed? Standard Definitions And Characteristics of Photons and Photonic Switching	6 g . 6	
2	Photo	onic Switching Physics	8	
3 A	Facto on	rs Driving Telecommunications technology towards photonic switching and	9	
	3.1 3.2 3.3 3.4 3.5 3.6	Traffic Demand and Growth vs. Technology Improvements Network revenue-bearing demand vs. capacity requirements Enabling Technologies and Industry Challenges for building Optical Networks Traffic Conclusions Switching Technology Growth Estimations Carrier Cost Considerations	. 10 . 12 . 12 . 13 . 12 . 13	
4	Techi	nology and Issues In Photonic Switching	. 14	
	4.1 4.2 4.3 4.4 4.5 4.5 4.5 4.6 4.7 4.8 4.9 4.10 4.11 4.12 4.13 4.13 4.13 4.13 4.13	Photonic Switching Building Blocks Planar Waveguide Micro Electro-Mechanical Systems (MEMS) Bubble Switching Free-Space Optical Switching Photonic Switching and Wavelength Conversion Electroholographic Optical Switching Soliton Light Bullets Photonic Crystals Bandgap Engineering Heterostructures Stimulated Raman Scattering and Amplification Non-linear Optics Current Issues In Photonic Switching 1 Wavelength Contention 2 Traffic Management and Control 3 Security .4 Additional Technology Considerations	. 14 . 14 . 14 . 15 . 16 . 17 . 19 . 20 . 22 . 22 . 22 . 22 . 22 . 22 . 22	
5	Emer 5.1 5.2 5.2.1	ging Photonic and Optical Switching Standards ITU-T Recommendation G.709 ITU-T Recommendation G.872 Interconnection and Interworking Between Different Administrative	. 28 . 30 . 33	
	5.2.2 5.3	Transport Functional Architecture of Optical Networks ITU-T Recommendation E.106 Description of an International Emergency	. 34 . 35	
		Preference Scheme (IEPS)	. 35	

5.4 AN	SI T1X1.5	
5.4.1	Transparency	
5.4.2	Limits	
5.4.3	Frequency Domain Performance Measurements	
5.4.4	3R Regeneration	
5.5 Inte	ernet Engineering Task Force (IETF)	
5.5.1	MPLS and GMPLS Extensions	
5.6 RF	C 2702 Requirements for Traffic Engineering Over MPLS	
5.6.1	Optical Interworking Forum (OIF)	
5.7 Stat	ndards Conclusions	
6 Conclusio	ons and Recommendations	

Figures

Figure 1 – FCC Based Bandwidth Growth Estimates	11
Figure 2 – MIT Image of a 3-Dimensional Crystal	20
Figure 3 - Photograph of five beryllium ions in a lithographically fabricated RF trap	24
Figure 4 – Quantum Tunneling Transistor	61
Figure 5 - Schrödinger's Equation	63
Figure 6 – Image Courtesy of Mike Matthews	65
Figure 7 – Sample Semiconductor Materials and the Color Spectrum	72

Tables

Table 1 - U.S. Optical Switching Components and Sub-Systems Markets (\$ millions)	13
Table 2 - Selected Photonic Switch Performance Definition	18
Table 3 - Sample Space-Switching Technologies	18

Appendices

Appendix A:	Acronyms	46
Appendix B:	References	49
Appendix C:	Standards References	50
Appendix D:	OIF Specifications	51
Appendix E:	Photonic Switching Terms	52
Appendix F:	Web Sites	55
Appendix G:	Photonic Switching Physics	57
Appendix H:	Suggested Readings	76

1 INTRODUCTION

The National Communications System (NCS) was established through a Presidential Memorandum signed by President John Kennedy on August 21, 1963. The memorandum assigned NCS the responsibility of providing necessary communications for the Federal Government under national emergency conditions by linking together, improving, and expanding the communication capabilities of the various agencies

In April 1984 President Ronald Reagan signed Executive Order (E.O.) 12472, Assignment of National Security and Emergency Preparedness (NS/EP) Telecommunications Functions, which broadened the mission and focus of the National Communications System (NCS). Since that time the NCS has been assisting the President and the Executive Office of the President (EOP) in exercising wartime and nonwartime emergency telecommunications and in coordinating the planning for, and provisioning of, NS/EP communications for the Federal Government under all circumstances. In this regard, the Office of the Manager, NCS (OMNCS), particularly its Technology and Standards Division (N6), always seeks to improve the Federal Government's ability to respond to national security and emergency situations. As part of this mission the N6 division identifies new technologies that enhance NS/EP communications capabilities and ensures key NS/EP features such as priority, interoperability, reliability, availability, and security are supported by emerging standards. In concert with this approach, the N6 manages the Federal Telecommunications Standards Program. Additionally, the N6 division directs efforts in both NS/EP management and applications services

Photonic switching is one of the technologies identified by the N6 division for potentially enhancing NS/EP communications. Accordingly, this report introduces photonic switching fundamentals and provides an overview and analysis of the technology for its potential to support NS/EP applications. The report also covers the basic terminology and the technological concepts used in photonic switching. It also includes a physics (e.g., quantum mechanics) primer appendix and relevant aspects from chemical and electrical engineering, which are beneficial for constructing an information decision framework regarding the adoption of photonic switching technologies. It also reports on activities to standardize photonic switching to define the interoperability of photonic and non-photonic interconnected networks where optical-electrical-optical (O-E-O or OEO) conversions are required. Finally, a review, summary, and recommendations regarding the application of photonic switching to support NS/EP requirements are provided.

Photonic switching systems are by their nature objects of interdisciplinarity¹. The fabrication of photonic switching devices requires the teamwork of physicists, chemical and electrical engineers, and other disciplines. The application of photonic switching technologies challenge the creativity of network designers, systems specialists, and field engineers. Technologies and research topics, especially those related to photonic switching, which have the potential of contributing to the development of faster telecommunications and computer processing systems continue to be placed at the center

of the world's attention. Research advancements are announced daily and cover a vast array of interdisciplinary areas. It is clear that with regards to cutting-edge technologies, such as photonic switching, that there is no existing body of pedagogical arguments from which to draw long range conclusions. The field of photonic switching is being driven at such a rapid pace that it is a challenge to decide which technologies to include and which technologies may eventually play only a minor role. It is difficult to pin-point the No one really knows the approaches that will withstand the test of time. What is clear, however, is that technology improvements that fall within the performance and cost advantage boundaries of photonic switching make this area an important NS/EP frontier.

1.1 Why is Photonic Switching Needed?

Photonic switching offers a number of advantages including: greater speed, dynamic network reconfiguration, reduced cost at points of high traffic demands, lower power requirements, no electrical conversion to perform switching, signal switching that is independent of data rates (transport transparency), and the scalability necessary for building future All Optical Networks (AON).

Current traffic projections suggest that near term communication networks for commercial and/or military applications will be required to carry combined voice, video, and various types of data traffic at rates of 100 Gb/s or higher². Today the speed of electronic circuits necessary to process the data is limited to \sim 30 Gb/s. The current theoretical limit of fiber optic systems is \sim 50 Thz. These potential improvements will be of extreme benefit to the OMNCS mission (section two of this report further explores the anticipated traffic demands).

Photonic switching presents an important advancement toward building an AON that would enable carriers to dramatically reduce the amount of time required to facilitate broadband services. It is estimated that service-provisioning times can be reduced by a factor of 10 and that costs can be driven down by a similar order of magnitude.

1.2 Standard Definitions And Characteristics of Photons and Photonic Switching

The American National Standard T1.523-2001 "Telecom Glossary 2000"³ provides the U.S. standard definition for photonic switching as: "The use of photonic devices rather than electronic devices to make or break connections within integrated circuits." This same standard succinctly defines a photon as: "a discrete packet, i.e., quantum, of electromagnetic energy." A photon has the energy (h), where (h) is the Max Karl Ernst Ludwig Planck's constant and is the frequency of the electromagnetic wave. For convenient reference, Planck's constant (h) is the constant of proportionality that relates the energy E of a photon with the frequency of the associated wave through the relation E = h; resulting in $h = 6.626 \times 10^{-34}$ joule•second.

Other characteristics of photons are of special importance and contribute to the overall performance improvements derived from photonic switching. Photons are particles that have no electrical charge and no mass; they have energy and momentum and these

properties allow photons to affect other particles upon collision. In a vacuum photons travel at the speed of light, which is 299,792,458 meters per second or 186,282,000 miles per second. Only particles without mass, such as photons, travel at the speed of light. At present, objects with mass such as electrons travel at speeds that are slower than the speed of light. For example, the fastest speed of electrons has been documented through a crystal of gallium arsenide at the rate of 14.4 million centimeters per second⁴. Important research progress into faster than light velocities was reported in 2000 when it was demonstrated that a pulse of laser light sent through a cesium vapor left the chamber before it had actually finished entering.⁵. Particle velocities that exceed the speed of photons are considered to be beyond scope of this report.

The energy of a photon is equal to the product of a Planck's constant multiplied by the frequency, or number of vibrations per second, of the photon. The equation for a photon's energy as E=hf, where (h) is Planck's Constant and (f) is the frequency. Photons with high frequencies, such as X rays, carry more energy than do photons with low frequencies, like radio waves. Photons that are visible to the human eye have energy levels around one electron volt (eV). The frequency of visible photons corresponds to the color of their light. Violet light photons are situated at the highest frequencies of visible light, red light photons have the lowest frequencies. Gamma rays, the highest-energy photons of all, have energies in the 1 GeV range.

In spite of the fact that momentum is most commonly considered a property of objects with mass, as previously stated photons also have momentum. Momentum determines the amount of force that an object exerts when it hits a surface. In classical non-quantum physics the behavior of objects we encounter in everyday life, momentum is equal to the product of the mass of an object multiplied by its velocity (the combination of its speed and direction). While photons do not have mass, they do exert extremely small amounts of pressure when they strike surfaces. Consequently, momentum has been redefined to include the force exerted by photons, commonly known as light or radiation pressure.

To remain consistent with the American standard definition for photonic switching we establish a central goal of remaining focused on rendering a detailed treatment of photonic switching and, where required, appendices to supplement the relevant fundamental building blocks of particle physics, quantum mechanics, and the other associated disciplines. However, for NS/EP purposes it is important to recognize that real world networks today do not operate exclusively within the province of photonic transmission or switching. Indeed, even where pure photonics is utilized to perform switching functions most real world systems today still incorporate associated network components that perform OEO conversions.

Today's commercial available photonic switching implementations can be viewed as the forerunners to the large scale AON systems that will be needed in the future. Clearly today's photonic switch implementations do offer important immediate benefits to the mission of the NCS such as providing the support necessary to handle very heavy traffic loads during NS/EP events. Therefore, an important goal of this report is to present photonic switching within the context of present day and near term real networking

capabilities that may be beneficial to the NCS without attempting to engage in technology forecasting. The very rapidly changing nature of this area of technology, however, does warrant the inclusion of some theoretical research information; especially where advances in physics, chemical and electrical engineering are most likely to impact future photonic switching development. Photonic switching solutions found in the marketplace today employ a wide range of solutions but there are very few photonic switching standards in place. Standardization of photonic switching interfaces is also experiencing rapid pace changes and further details regarding current standardization efforts are subsequently addressed in this report.

2 PHOTONIC SWITCHING PHYSICS

If the laws of physics were the only consideration in network design, optical networks are clearly superior to electronic networks. The speed of electrons through a wire is approximately 2×10^8 . The speed of photons through a fiber optic channel approximates 3×10^8 ; outside a "vacuum" light cannot achieve its maximum speed. However, the order of magnitude difference in speed means that data traveling through an electronic network will be measured in megabytes per second (Mb/s) verses terabytes per second (Tb/s) in photonic networks. The switching time of the fastest GaAs (see Appendix G) transistor is about 20 picoseconds. The switching time for a photonic transistor is 1 picosecond or less. The power requirement for an electronic switching component is about 1 microWatt, whereas the same power requirement for a photonic switching component is measured in nanoWatts.

Today we are experiencing the early, yet rapid, affects of "photonization⁶" of greater portions of the worldwide infrastructure of telecommunications networks. To better understand the significant changes that this transition will bring to the NS/EP environment as it unfolds, a high level overview of electronic verses photonic switching physics is beneficial.

One of the most important fundamental theories that have guided electron based networks was the classical 1948 paper by Claude Elwood Shannon titled: "The Mathematical Theory of Communication⁷." His theory of communications was developed in the context of linear channels with additive noise, which adequately describes electromagnetic propagation through wires and cables. The beauty of Shannon's law is in the fundamental simplicity of its linear characteristics,

C=B*log₂(1+S/N) where

C = achievable channel capacity; B= Bandwidth of the line in Hz; S= Average signal power; N=Average Noise Power; S/N + Signal to Noise Ratio. S/N is usually measured in decibels (dB) where $dB = 10*log_{10}(S/N)$. Fading channels or those with multiplicative noise has been studied for applications like wireless communications. Wireless channels remain less manageable than additive noise channels.

With the introduction of practical applications for optical fibre communications we have been confronted with the physics of a nonlinear propagation channel, which in many ways continues to pose major challenges to our understanding. Current research with photonic crystals and bandgap engineering clearly indicates that this difficulty extends into the physics that will ultimately serve optical switching requirements. Unlike electron based networks, optical networks are comprised of input-output relationships that are obtained by integrating a nonlinear partial differential equation that may not be represented by an instantaneous non-linearity. Channels where the non-linearities in the input-output relationship are not instantaneous are much less understood and thus present significant barriers to the progress of new implementations. The understanding of such nonlinear channels, especially in association with memory storage, is a fundamental requirement because communication rates through optical fibres are increasing exponentially. There are several non-linear effects, present in varying degrees at high data rates, and thus are important considerations in the progression of optical switching systems and AON. These factors include: chromatic dispersion, polarization mode dispersion, four-wave mixing, self-phase modulation, and cross-phase modulation. These effects can combine in ways that make theoretical analysis, and thus operational predictions, extremely difficult to anticipate.

A more lengthy treatment of this subject area, with a more concentrated emphasis on relevant physics background and research, is included for the interested reader in Appendix G of this report. However, the reader is alerted to the fact that frontier research areas of optical physics are changing at a pace far more rapidly than can satisfactorily be statically represented. The more conservative, simplistic, and practical approaches that can easily be implemented to achieve today's photonic switching requirements are highlighted in section 4 of this report.

3 FACTORS DRIVING TELECOMMUNICATIONS TECHNOLOGY TOWARDS PHOTONIC SWITCHING

Any inquisitive reader can easily find numerous projections of anticipated growth in the demand for telecommunications bandwidth worldwide. In addition to worldwide population growth and modernization efforts in even the most economically disadvantaged countries, clearly a number of new technologies have contributed to the rapidly increasing demand for bandwidth; especially within the United States. The Personal Communications Service (e.g., wireless voice) era came about just as the rapid increases in data communications requirements associated with the Internet evolved. The advent of Internet technologies have been repeatedly identified as sources of substantial bandwidth requirements through at least 2010. This section considers the need for deployment of optical networks as a means to facilitate the growth demand for bandwidth

and as a solution to the ever increasing competition and economic pressures to reduce operating costs by carriers.

3.1 Traffic Demand and Growth vs. Technology Improvements

Optical components and photonic switching technology developments offer the promise of vast increases in bandwidth, speed, and reduced operating costs. However, the existence of this technology alone does not necessarily imply that its implementation in wide-area communications networks will result in either rapid or widespread deployment.

The speed and cost advantages associated with U.S. photonic switching systems is directly related to the installed base and capacity of fiber. Thus, an increase in U.S. fiber installation provides an expansion of capacity by providing an increase in the total of installed fiber miles and the improvement associated with the newest fiber technology. It is therefore relevant to note that the growth rate in fiber miles installed in the U.S. actually reflected a decrease during the most relevant decade. The 1990's started with an installation gain of 25% per year but by the end of the decade this rate of growth had fallen to approximately 18% annually. The overall decrease in fiber mile installation has been attributed to the local bell operating companies. The bell operating companies are responsible for approximately 66% of total U.S. fiber miles.

During the 1995-1996 timeframe the Internet traffic bandwidth growth demand was unusually dramatic. However, the total Internet bandwidth required accounted for only about 2.1% of the total RBOC interoffice bandwidth by 1998. Although Internet backbone traffic grew 1,000% between 1995 and 1996, the growth rate fell to about 100% in 1997 and has remained essentially stable at this rate through present day measurements⁸.

The aforementioned actual statistics recorded for the past decade contrast not only with the projections of industry leaders in the early 1990s, but even with some of the later perceptions and beliefs of a bandwidth explosion. For example, Reed Hundt, former Chairman of the Federal Communications Commission (FCC), in his book titled: "You Say You Want a Revolution," "In 1999 data traffic was doubling every 90 days, as connected personal computers spread across the globe." A rate that doubles every 90 days would equate to an unsustainable annual growth rate of 1,663% per year. An early citation of a similar statistic was contained in the U.S. Department of Commerce's April 1998 report, "The Emerging Digital Economy," which stated, "...one of the largest Internet backbone providers, estimates that Internet traffic doubles every 100 days."

The widespread reporting of such statistics was at least, in part, responsible for creating the belief that a new electronic commerce economy was unfolding and that it was being driven by a communications bandwidth explosion in the U.S. Today, the most common consensus is that some of the Internet traffic growth estimates were based upon unique methods of traffic measurement. Consideration of more comprehensive and better documented evidence suggests a much different picture of bandwidth growth. The preponderance of evidence suggests that that there has not been a dramatic upsurge in total U.S. bandwidth in use in the latter part of the 1990s and early 2000.

Domestically, the FCC's statistical evidence is consistent with an annual growth of approximately 8% per year for voice and approximately 34% per year for transaction data. International voice traffic has been growing by 17% per year and transaction data traffic is growing at 52% per year. These traffic patterns, combined with Internet traffic, suggest total revenue bearing long-distance traffic in the United States of 214 Gb/s during the latter part of the 1990's. This was comprised of 166 Gb/s of voice traffic, 23 Gb/s of transaction data traffic, and approximately 25 Gb/s of Internet traffic.



Figure 1 – FCC Based Bandwidth Growth Estimates

The graph depicted in Figure 1 includes all of the average revenue-bearing traffic, which means that the projections are smaller than the total U.S. capacity required to support the demand. The actual capacity required to satisfy the depicted traffic demand is further described in section 3.2.

Today's technology developments in optical components unquestionably have made dramatic increases in the amount of bandwidth that is possible to achieve. To get a general sense of current technology, consider that a sample optical transport system available for volume shipments in the past twelve months using dense wavelength division multiplexing (DWDM), without OEO regeneration can provide a total of 560 Gb/s across a single 3,600 km optical fiber. Routers with a rich set of packet-forwarding functions have been produced that provide 160 Gb/s throughput using equipment that is about half the size of an average telecom equipment rack. For example, one all-optical wavelength router that became commercially available in the past twelve months can support 256 40 Gb/s data channels.

3.2 Network Revenue-Bearing Demand vs. Capacity Requirements

Figure 1 allows us to consider a number of implications on the revenue generated and the capacity requirements of networks. Where, for example, an industry based revenue centric model has been employed for analysis it has been shown⁵ that the average revenue-bearing traffic has to be scaled to include a peak working and protection capacity, overhead, and various other network inefficiencies. If we assume a peak to average traffic ratio of five, and apply a restoration capacity of 70%, add an additional 25% capacity for inefficient channel loading at two different multiplexing levels, it is reasonable to project that the required U.S. capacity is approximately 15 times the average revenue-bearing traffic demand. For a less efficient network this factor would have to be even higher. If it is reasonable to expect that future traffic growth will continue to be dominated by the Internet, which has longer connection distances than voice traffic, it is very possible to understand that capacity will be significantly impacted if the change in the future traffic mix continues to shift from voice to Internet traffic.

3.3 Enabling Technologies and Industry Challenges for building Optical Networks

The requirements for optical networks include: transparent long-haul transmission, reconfigurability, scalability, and multi-vendor interoperability. The technologies needed include: smart wavelength-routing architectures, wavelength add/drop multiplexers, and optical cross-connects. While a national-scale transparent network can not be affordably achieved today, the concepts of long transparent reach managed on a wavelength basis are likely to become a reality as costs drop. In this architecture a significant reduction in the necessity to regenerate channels can be realized. For a viable network architecture, one needs to include the operators' needs for network management, capacity growth, service flexibility, and survivability. With a continued move from voice to data networks some of this functionality can be moved to the optical layer. This shift in functionality to the optical layer results in a more flexible layer but will require more complexity as well. Industry challenges include accommodating the growth in traffic and network complexity, as well as providing technological solutions for optical performance monitoring and optical network management.

3.4 Switching Technology Growth Estimations

Optical Switching Components and Sub-Systems Markets			
	2001	2002	2005
Mechanical	63.3	69.0	65.4
2D MEMS	43.0	95.3	298.0
Liquid Crystal	20.5	52.3	199.3
Waveguide and sold state	18.2	41.2	202.0
OEO	7.6	14.7	32.4

Industry estimations for the growth of various switching technologies over the short term are available and suggest the following trends:

3D MEMS	0.0	25.3	297.2
TOTAL	152.6	297.7	1094.3

Table 1 - U.	S. Optical Switching	Components and Su	b-Systems Markets	(\$ millions) ⁹
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From the data in Table 1 it is clear that mechanical switching systems will not disappear within the near future. It should also be noted, for example, that today's Micro Electro-Mechanical Systems (MEMS) do in fact rely on OEO conversions upon exit from the photonic switching function.

3.5 Carrier Cost Considerations

Insight into the benefits that photonic switching has to offer can be obtained from a brief examination of how carrier backbones operate today. Presently, in carrier backbones traffic moves as pulses of light over fiber, but predominantly the pulses have to be converted back into electrical signals in order to switch them from one fiber to another at junction points. On long routes, the light pulses need to be regenerated electrically approximately every 200 miles, depending on the fiber type used. Without regeneration the light pulses can spread into each other, making it impossible for the receiving equipment to distinguish discrete signals from each other. The electrical regeneration required is in addition to optical amplification of the signal, which is carried out using an Erbium-doped Fiber Amplifier (EDFA). On a long distance route, the need to regenerate signals can add up to a lot of OEO conversions. For example, a connection between New Your and Los Angeles could require as many as 20 to 30 signal regenerations. At each regeneration station, dense wave division multiplexing (DWDM) equipment is required to terminate wavelengths, and transponders are needed to convert the optical signals to electrical. Then the signals are re-shaped, re-timed, and re-synchronized and sent back out through additional transponders and DWDM equipment to the next segment of the connection.

The signal regeneration process is expensive not only in additional equipment and spare parts but also in rack space, personnel, training, and maintenance costs. Additionally, the large number of OEO conversions required makes it more difficult to take advantage of technology innovations quickly because in many cases it is necessary to upgrade all 20-30 sites just to increase the capacity of a single route.

3.6 Traffic Conclusions

Traffic growth for Internet applications is likely to continue to be the dominant area of bandwidth growth requirements in the foreseeable future, thereby creating a greater demand for a new optical layer architecture. The value of an optical layer architecture is beginning to be realized within the user community. One important difference between the traffic patterns generated by Internet connectivity is that on average these connections are significantly longer in duration than conventional voice connections. This creates an opportunity for network cost savings by using ultra-long reach systems with optical switching technologies to route and manage those connections.

4 TECHNOLOGY AND ISSUES IN PHOTONIC SWITCHING

4.1 Building Blocks of Photonic Switching

As indicated in Table 1 there are several different market technologies available today that can be used to develop the fundamental building blocks required for photonic switching. Present day commercial offerings of photonic switching systems are limited in terms of scalability. However, the existing product offerings are sufficiently attractive for service providers, cutting edge organizations, and organizations with very large scale requirements. However, it should be noted that there is no present indication that today's technologies will reliably scale to handle very large switching requirements. Currently, there exists a number of all-optical switching devices, including the birefringent-fiber polarization switch, the optical-fiber Kerr gate, the two-core-fiber nonlinear directional coupler, the birefringent single-core-fiber, the nonlinear fiber-loop mirror, the solition dragging logic gate, the bistable nonlinear optical switching device, the spatial soliton beam switch in a planar waveguide, the nonlinear polarization switch in a semiconductor waveguide including a multiquantum well waveguide, the semiconductor interferometer switch, the nonlinear Bragg semiconductor waveguide switch, and the bistable optical switch. This section provides a brief overview of the most dominant photonic switching techniques, to include (1) planar waveguides, (2) micro electro-mechanical systems (MEMS), and (3) bubble switching. Additionally, this section also identifies several promising technologies that currently may be characterized as belonging to the research and development arena. One clear point is that virtually all current photonic switching technologies are at an early stage of development. Therefore, it is premature to say, at this time, which technology will be widely deployed.

4.2 Planar Waveguide

A planar waveguide is also known as a slab-dielectric waveguide. A formal definition for the term may be found in the ANSI T1.523-2001 "Telecom Glossary 2000." Essentially it is "an electromagnetic waveguide that consists solely of dielectric materials."

A planar waveguide essentially creates glass fibers on silicon chips and routes light from one of these fibers (these are the waveguides) to another. The advantages that an optically-confined planar geometry can bring to laser devices includes: high optical gains, low laser thresholds, compatibility with diode pump lasers, excellent thermal management, fabrication techniques that can be applied to a broad range of materials, and the possibility of integrating functions for highly-compact waveguides.

4.3 Micro Electro-Mechanical Systems (MEMS)

This technology uses tiny, moveable mirrors that are embedded into semiconductor materials. The scalability that MEMS offers comes from using semiconductor

technology. MEMS embeds large arrays of microscopic mirrors in silicon and enables each mirror to be tilted to deflect individual beams of light.

Currently, vendors have successfully produced an array of 256 x 256 mirrors in a one inch square piece of silicon. This results in a 256 x 256 port switch. It is believed that over time this technology can be refined to produce a 1012×1012 port switch for use in optical cross connects.

One historical downside of MEMS is that a lot of light gets lost. The technology was originally designed for very large screens such as those used at sporting events. The technology was then modified for use in photonic switches. Light signals leaving MEMS are so weak that they must be electrically regenerated on exit. The weak photonic signals are presently a tradeoff to achieve a relatively large-scale optical switch. Research scientists at the Massachusetts Institute of Technology (MIT) have invented what some are calling the perfect mirror because it is able to reflect light at any angle with virtually no loss of energy. One potential application identified for the MIT solution is the improvement of MEMS performance¹⁰.

Some critics have expressed concern that, over time, the moving mechanical parts in MEMS products could wear out or jam in place over time. The point is often raised that telephone companies moved away from mechanical switches a long time ago. The rate at which mechanical systems jammed was an important factor motivating the evolution of that technology and it's the same reason that is causing some people express concerns about the long term future of a MEMS switch in the central office.

Presently there are fully integrated, three-dimensional MEMS optical switching systems that have been offered in the marketplace. These solutions can be used as the core of all-optical cross connects and add/drop multiplexers. Unlike their electronic switch counterparts, which are typically limited to bit-rates of 10 Gb/s, MEMS switching technology is able to handle virtually any type of high bandwidth signal in today's 10 - 100 Gb/s environments. MEMS technology promises to relieve many of the bottlenecks found in optical network switching. MEMS technology by definition supports scalability by allowing any data rate or transmission protocol to travel across the switch.

4.4 Bubble Switching

With bubble photonic switching systems the switching device itself consists of a planar lightwave circuit with intersecting silica waveguides. At each intersection, a trench is etched into the waveguide. The trenches are filled with an index-matching fluid that enables transmission in a normal condition. To direct light from an input to another output, a thermal inkjet element creates a bubble in the fluid at the intersection between the input waveguide and the desired output waveguide, reflecting the light by total internal reflection.

Industry announcements of bubble based photonic switching systems intended to scale up to 512-by-512 ports, with each port operating at speeds of 10 Gb/s have been issued and

it has been projected that by 2004 bubble photonic switching systems will scale to as many as 4,000 x 4000 ports; each operating at 40 Gb/s.

Bubble photonic switching advocates point out that the bubbles act like mirrors without suffering the drawback of having tilting mechanisms that could jam or wear out over time. A basic bubble photonic switching building block can, for example, be a 32-by-32 port switch on a chip. Inside the chip, there is a matrix of microscopic channels filled with a special liquid, through which light travels. At each intersection point, a bubble jet pen can heat the liquid so that it boils and creates a tiny bubble. This acts like a mirror, deflecting light onto the intersecting path. The 32-by-32 port modules can be linked together to create large scale switches.

Bubble jet technology has been used for many years in printers. The manufacturing process is well proven, and the jet pens routinely blow bubbles without any difficulties. The counterpoint to this view is that the bubbles used in printers only have to last a split second before they're allowed to collapse. In an all-optical switch, they could potentially be required to be maintained indefinitely. This implies that the pen would have to continue heating the fluid and raises a question mark about whether this would increase the temperature of the fluid in adjoining channels – and whether that might interfere with their light-carrying properties.

An all optical and transparent bubble platform offers bit rate and protocol independence. Current bubble photonic switching systems can be used to construct large N x N optical cross connects, with loss on the average 5 of dB fiber-to-fiber for a wavelength selective crossconnect and 15 dB for a 512 x 512 wavelength interchange. Systems have been built that are transparent at 1300 and 1550 nm wavelength bands.

4.5 Free-Space Optical Switching

Free-space optical interconnects use the dimension perpendicular to the planes containing the electronics, transmitters, and receivers, rather than concentrating the optical energy via wavelenguides. The main advantages of using free-space optical interconnects relative to electronic interconnects include:

- Lower power dissipation along with higher interconnection densities;
- Greater reliability, cost reduction, and improved utilization of chip areas for processing;
- Reduced crosstalk and electromagnetic interference sensitivity
- Improved clocking and signal timing

Space switching involves changing the path of an optical signal without changing either the wavelength or color. There are a number of performance metrics that must be satisfied in order to pass the signal through without alteration. These metrics include the thermal stability, size, power requirements, and reliability. Primary limitations with free-space switching are the alignment and packaging of optical transmitters, optical channel elements, and optical receivers; the optoelectronic transmitter and receiver cost, reliability and fabrication; and the loss of optical power along the interconnection path. The delay of the signals, although constant, is unlikely to be less than in electronic interconnections.

The limitation in the number of ports for a single-chip switch is determined by the available chip size and the comparatively long length of the switching elements, which is in the order of hundreds of micrometers. The uncertainty about implementing switching fabrics larger than 100×100 , may leave photonic space switching best suited for cross-connect applications at the present time. Cross-connect applications involve connections between terminal blocks on the two sides of a distribution frame.

4.5.1 Photonic Switching Performance and Technologies

In order for a photonic switching signal to pass through the switch unaltered, the switch design must effectively address a number of performance metrics. Naturally, cost, manufacturability, thermal stability, reliability, and physical characteristics, such as size and packaging, are always important. Additionally, Table 2 identifies some of the key photonic switching performance metrics.

One of the practical photonic switching problems to solve is that no fiber can carry more than one signal at a given wavelength. Consequently, if two signals at the same wavelength need to be switched to the same output fiber, they will both contend for that wavelength, and one will be blocked. All-optical wavelength conversion addresses this contention problem. Wavelength conversion, as the name implies, translates or converts the input wavelength to another color to match the desired output, within the optical domain. In an optical cross-connect OXC), wavelength conversion could be used on the fly to avoid wavelength contention by taking advantage of an available output "slot." The switched signal wouldn't be blocked because the wavelength conversion device would alter the signal's wavelength to match an "open" output if the originally desired wavelength were taken. Consequently, wavelength conversion would enable nonblocking networks with improved efficiency. A Photonic Cross-Connects (PXC) is defined as an all-optical device (i.e. no OEO conversion) and an OXC as a bit-rate transparent device (i.e. providing OEO conversions at each interface).

Selected Photonic Switch Performance Definition		
Metric	Description	
Cross-talk	Degree to which one channel affects an adjacent one	
Drive Voltage	The electrical voltage required to control the switch	

Extinction	Degree to which an "open" switch lets no light through. A switch
	with a good extinction ratio is analogous to a window shade that
	keeps a room totally dark
Insertion Loss	Reduction of the strength of the signal, attenuation
Polarization	Degree to which the polarization of the photonic signal is altered.
Dependent Loss (PDL)	PDL introduces errors at the optical receiver
Speed	Time required to complete the switching function completely

Both public and private organizations are presently working on photonic switching and wavelength conversion, using a variety of technologies. At this point in the development process it does not appear that there will be any one-size-fits-all solution. A handful of technologies will mature and succeed. Table 3 lists some of the current technologies that are more viable prospects for the near term, while those that are predicated on breakthrough material advances will invariably take a longer time to mature.

Selected Space-Switching Technologies		
Technology	Comments	
Electro-mechanical	Performs well in terms of most performance metrics, but size, reliability, scalability, and cost remain issues	
Indium Phosphide	Attractive for some applications and very fast, but cost is a hurdle	
Lithium Niobate	Really shines in terms of speed, but PDL and loss can be problems	
Liquid Crystal Display (LCD)	Some proprietary solutions are promising. Still, speed, temperature, humidity, and PDL can be problematic	
Micro- Electromechanical Systems (MEMS)	Conceptually a very attractive solution because it leverages well- understood silicon semiconductor manufacturing techniques, but not mature. Reliability and interconnect issues still need to be overcome.	
Polymer	Advantageous from a cost perspective, but fundamental material issues remain	
Silica	Good in terms of loss, but can be slow	
Silicon	High integration potential, but cross-talk, loss, and speed can be issues	

Table 3 - Sample Space-Switching Technologies

Thus there are several market choices available today with respect to the building blocks required for photonic switching. So far the photonic switching systems currently available for purchase have limitations in terms of scalability. While existing product offerings are attractive for leading edge technology consumers is not clear which of today's technologies, if any, will handle very large scale switching requirements. This section provides a brief overview of current photonic switching technologies including:

(1) planar waveguide solutions (2) micro electro-mechanical systems (MEMS) (3) bubble switching.

4.6 Electroholographic Optical Switching

The dream of a speedy all-optical network has so far been thwarted by the widely recognized bottleneck in today's networks where optical switches must convert data to an electrical signal to go from one optical fiber to the next, and then convert the data back to optical to speed it on its way. This conversion requires costly and bulky equipment, and when it is necessary to scale up to the high-bandwidth data streams demanded by the latest optical networks, these switches quickly loose their cost-effectiveness. A better solution is an all-optical device that can affordably switch gigabytes of data without conversion.

Optical switching devices have been constructed from arrays of tiny mirrors, liquid crystals, ink-jet bubbles and other technologies. One of the other solutions presently under development employs the use of holograms. This process involves the creation of ribbon like holograms within crystals that are arranged in rows and columns to form a trellis structure. When electrically charged, the holograms selectively deflect specific colors onto new paths, while the rest of the light wavelengths pass through unaffected.

Devices have been build that can perform switching functions in as little as 10 nanoseconds. It is believed that future versions will be able to perform even better. Although present optical switches are judged more by the number of wavelengths they can process rather than the switching the speed the speed of electroholographic optical switching may be much more attractive when intelligent optical routers that can analyze and optimize the path of individual data packets are deployed.

4.7 Soliton Light Bullets

Optical solitons are special solitary waves that are orthogonal, in the sense that when two of these waves cross one another in the medium, their intensity profiles are not altered, and only phase shifts occur as a result of the interaction. Each wave continues to travel as an independent entity.

A "light bullet" is a three-dimensional soliton that is self-guided in the two transverse spatial dimensions and in the direction of propagation due to the balance of material anomalous group-velocity dispersion (AGVD) and nonlinear self-phase modulation (SPM). The term light bullet comes from the fact that it can be though of as a tiny bead of light propagating long distances without change. Numerical simulations and stability analysis suggest that index saturation or higher-order nonlinearity is required for the existence of propagating light bullets.

Light bullets have several key characteristics. They have great potential for massive parallelism in space and pipelining in time. Light bullets also operate on the scaling law

that suggests that smaller light bullets require less energy. Thus a light bullet lasting 100 femtoseconds could carry as much data, with far less energy required, than a 200 femtosecond light bullet.

The NASA Ames Research Center acquired a patent for an invention that describes devices using light bullets to perform ultra-fast, all-optical switching. The technology enables all-optical switching in a solid state device, such as a planar slab waveguide made of highly nonlinear optical materials including: highly non-linear glasses, semiconductor crystals, and/or multiple quantum well semiconductor materials. It uses optical pulses in the planar waveguide, and these pulses are stable and self-supporting due to nonlinear effects that balance the effects of dispersion and diffraction, i.e. these pulses are light bullets. The advantages are the potential for massive parallelism, in space, and pipelining, in time.

The Ames researchers have performed computer simulations and developed designs for an all-optical switch made of highly nonlinear materials. In the NASA switch configuration, light bullets propagate through, and interact nonlinearly with each other within a planar slab waveguide to selectively change each other's directions of propagation into predetermined output channels. The multiple quantum well semiconductors are of particular interest since they require far less power (below 1 watt) of light intensity in order to support the light bullet propagation. The resulting performance is predicted to enable low power, high speed 100 femtosecond light bullet switching in a small device, that should be easy to manufacture using current semiconductor manufacturing techniques. Soliton switching occurs because propagating light bullets interact in such a way that they are deflected into different output channels from the waveguide.

4.8 Photonic Crystals



Figure 2 – MIT Image of a 3-Dimensional Crystal

At the most fundamental level of photonic switching systems, it is necessary to employ a material that can provide as much control over light as possible. The importance of photonic crystals to photonic switching is paramount. A photonic crystal is a periodic arrangement of atoms or molecules. It is a crystal lattice that results when a small basic building block of atoms or molecules is repeated in space. Of special importance is that

the lattice can be built to introduce gaps into the energy band structure of the crystal such that a photonic band gap is constructed. If the crystal lattice potential is strong enough the gap can be made to extend in all directions resulting in a complete band gap. The properties of crystals have been exploited such that there are one, two, and three dimensional photonic crystals being developed. Since photonic crystals are not a naturally occurring phenomenon; it is necessary to build them. Chemical engineers and other scientists are aggressively pursuing this area of technology in order to best facilitate the manipulation of photons to control electromagnetic radiation for potential telecommunications applications that include: optical switching, micro-fabricated lasers, waveguides, and light-emitting diodes.

To build a photonic crystal requires the creation of a periodic structure from dielectric material. The dielectric serves as an electrical insulator or in which an electric field can be perpetuated with a minimum loss in power. The photonic material must be arranged in a lattice structure that repeats itself identically and at regular intervals. Only when the assemblage is precisely made, the resulting crystal can have a photonic bandgap. A photonic bandgap provides a range of forbidden frequencies within which a specific wavelength is blocked and light is reflected. With the exception of the bandgap, a properly constructed photonic crystal will transmit wavelengths of light up and down the electromagnetic spectrum. Today, it is possible to predetermine the bandgap by engineering the lattice spacing of the photonic material to match the wavelengths that needs to be blocked. This has significantly enhanced the ability to control and manipulate light by sending it down assigned routes and around loops and bends.

Advancements in the area of photonic crystals are an ongoing process. For example, a scientist working under funding from the National Science Foundation discovered a new process enables the "cutting" of 3 dimensional arrays of holes in a polymer material. Essentially this process creates an orderly pattern of air bubbles throughout a polymer film by using a simple solvent. By controlling the polymer, solvent, humidity and flow of air across the polymer, the condensation of tiny uniform water droplets is created. The droplets sink into the polymer film and the process repeats itself on its own until the film is filled with a three dimensional array of water bubbles. When the solvent and water evaporate, they leave behind a polymer scaffold with a lattice of equal-sized air bubbles.

Work on photonic switching crystals today is primarily focused on three-dimensional, periodic dielectric structures with lattice spacing on the order of the wavelengths of light. Figure 2 illustrates a three-dimensional crystal. A two-dimensional photonic crystal is periodic along two of its axes and homogeneous along the third. The simplest possible photonic crystal is comprised of alternating layers of material with different dielectric constants. Three-dimensional crystals continue to cause a great deal of excitement because of their capability to create a complete band gap. This is a frequency range for which no light can propagate in a crystal in any direction, causing radical modifications of the density of radiative states. The result is a quantum-optical phenomena such as spontaneous emission inhibition or localization.

4.9 Bandgap Engineering

A large number of semiconductor materials can be used to manufacture quantum structures; see Appendix G Figure 7. In addition, one can "mix" different semiconductors with favorable properties into an alloy. This "play" with input parameters is usually referred to as bandgap engineering. This opens fascinating possibilities for fabrication of e.g. laser structures: One can select semiconductor materials in such a way that the laser emits at an almost arbitrary wavelength. More specifically, it is possible to design and construct photonic crystals with photonic band gaps that prevent light from propagating in certain directions with specific energies. If, for some frequency range, a photonic crystal reflects light of any polarization incident at any angle then it is classified as a complete photonic bandgap. In the crystal, no light modes can propagate if they have a frequency within that range. In order to create a material with a complete photonic band gap, it is necessary to arrange contrasting dielectrics in a lattice that is periodic along three axes.

4.10 Heterostructures

Heterostructures are the building blocks of many of the most advanced semiconductor devices presently being developed and produced. They are essential elements of the highest-performance optical sources and detectors, and are being employed increasingly in high-speed and high-frequency digital and analog devices. The usefulness of heterostructures is that they offer precise control over the states and motions of charge carriers in semiconductors.

For photonic switching purposes, a heterostructure can be defined as a semiconductor structure in which the chemical composition changes with position. The simplest heterostructure consists of a single heterojunction, which is an interface within a semiconductor crystal across which the chemical composition changes. Examples include junctions between Gallium (Ga) Antimony (Sb) [GaSb] and Indium (In) Arsenic (As) [InAs] semiconductors, junctions between Gallium (Ga) Arsenic (As) [GaAs] solid solutions, and junctions between Silicon (Si) and Germanium (Ge) Silicon (Si) [GeSi] alloys. Most devices and experimental samples contain more than one heterojunction, and are thus more properly described by the more general term heterostructure. Further examples of solid state physics compositions and their usage within the visible light spectrum can be found in Appendix G Figure 7.

4.11 Stimulated Raman Scattering and Amplification

The ANSI Telecommunications Glossary provides the primary definition for Raman scattering as "the generation of many different wavelengths of light from a nominally single-wavelength source by means of lasing action and interaction with molecules, thereby creating many different excited molecular energy levels that produce photons of various energy levels." Raman scattering is primarily concerned with lattice dynamics. High pressure Raman measurements are concerned with shifts in the frequencies of

vibrations due to changes in inter-nuclear spacing coupled with the harmonic nature of inter-atomic and intra-molecular interactions.

If a phase transition occurs, the Raman selection rules, which are dependent on the crystal and molecular symmetries, will also change and new spectral features, characteristics for the new lattice, will appear. Thus this method is not only of great help in elucidating crystal structures, but can also be used as a method of qualitative analysis in determining the phases of small thin section areas without destroying them.

Optical amplification process throughout the actual transmission fiber in an optical network, caused by a carefully selected pump-laser wavelength scattering from atoms in the fiber and changing its wavelength to that of the optical signal.

The principle of Raman scattering is that a lower wavelength pump-laser light traveling down an optical fiber along with the signal, scatters off atoms in the fiber, loses some energy to the atoms, and then continues its journey with the same wavelength as the signal. Therefore the signal has additional photons representing it and, hence, is amplified. This new photon can now be joined by many more from the pump, which continue to be scattered as they travel down the fiber in a cascading process.

The ANSI Telecommunications Glossary 2000 also provides us with a primary definition for Raman amplifier as "a device that amplifies an optical signal directly, without the need to convert it to an electrical signal, amplify it electrically, and reconvert it to an optical signal." It is usually accomplished as "distributed' amplification" — that is, it happens throughout the length of the actual transmission fiber, rather than all in one place in a small box as with an EDFA for example. So into the same fiber that is carrying the signal, you can add a high-power pump wavelength, of a few watts of power, which will amplify the signal along many kilometers of fiber until the pump signal eventually fades away. If you insert the pump at the beginning of the fiber, that is known as forward pumping or co-pumping. Better performance can usually be achieved, however, by pumping from the far end of the fiber — known as backward pumping or counterpumping — or by a combination of the two (co-counter pumping). If you have several different signal wavelengths in a system, then usually several different pump wavelengths will need to be used together to achieve the required amplification at every wavelength. As with EDFAs, gain flatness is also an issue that needs careful design to achieve. Raman amplification is a useful technology for optical networks. Several designs of submarine systems incorporate a form of Raman amplification in order to extend the transmission distances possible.

4.12 Non-linear Optics

The field of nonlinear fiber optics has grown substantially since the late 1980's with particular attention being paid to the importance of nonlinear effects in the design of optical fiber communication and switching systems. Atomic, molecular, and optical physics has long been at the forefront of the manipulation and control of individual quantum systems; now with particularly spectacular developments resulting from the

trapping and cooling of single electrons, ions, and neutral atoms. These advances are enabling realizations of conditional quantum dynamics at the single-quantum level for the implementation of quantum logic. Nonlinear optics has been extended into the



Figure 3 - Photograph of five beryllium ions in a lithographically fabricated RF trap

(Photograph courtesy of the National Science Foundation)

domain of single atoms and photons, leading to a demonstration of a quantum phase gate in which one photon induces a conditional phase shift on another via their mutual interactions with an atom in an optical cavity. Single trapped atoms have been cooled to the zero point of motion, and a quantum gate has been implemented by conditionally exciting a single phonon in an ion trap. Figure 3 is an NSF photograph that depicts five beryllium ions in a lithographically fabricated trap.

In a linear system, the output is directly proportional to the input. So if the input doubles, the output doubles. In a nonlinear system, we no longer have a straight-line relationship. Instead we have a curve, and the output does not scale linearly with the input. In the case of a nonlinear optical transmission network, if the input signal doubles in power then the output is less than double

The reason nonlinear transmission effects are becoming more prominent now is that with the advent of WDM systems, and higher and higher bit-rates being used, the amount of optical power within fibers is increasing. And it is at high optical powers that nonlinear effects start to become noticeable, whereas in low bit-rate systems they can often be ignored completely.

In fibre transmission systems there are two categories of nonlinear effects: Kerr effects and scattering effects. The first consists of three phenomena. In an optical fiber the core in which the optical signals travel has a specific refractive index that determines how light travels through it. However, depending upon the intensity of light traveling in the core, this refractive index can change. This intensity-dependence of refractive index is called the Kerr effect. It can cause "self-phase modulation" of a signal, whereby a wavelength can spread out onto adjacent wavelengths by itself. It can also cause "crossphase modulation," whereby several different wavelengths in a system can cause each other to spread out.

There are two nonlinear scattering effects: (1) Raman and (2) Brillouin. Both are inelastic processes in which part of the power is lost from an optical wave and absorbed by the transmission medium. The remaining energy is then re-emitted as a wave of lower frequency. Raman and Brillouin scattering processes can become nonlinear in optical fibres due to the high optical intensity in the core and the long interaction lengths afforded by these waveguides. Stimulated Raman scattering involves light losing energy to molecules in the fiber and being re-emitted at a longer wavelength; due energy loss. In stimulated Brillouin scattering light in the fiber can create acoustic waves, which then scatter light to different wavelengths. Due to nonlinear effects signals can be mixed making it difficult to distinguish them at the end of the system.

In photonic switching systems non-linear optics are currently being investigated with respect to the use of photonic band gap structures with a defect. Comparisons with an optical switch using a perfect non-linear quarter-wave reflector shows that introducing a defect can improve performance.

4.13 Current Issues In Photonic Switching

A number of current issues in photonic switching present challenges with respect to use during NS/EP conditions at the present time. Commercially, terabit per second Tb/s switches and routers are available today. However, numerous issues still exist in the design of such high-speed switching systems. Link speeds are now approaching, and exceeding, memory bandwidths complicating buffer designs. The trend of growth in link speeds exceeding increases in memory bandwidth is expected to continue. In addition to very high-speed links and large switching capacities, future very high-speed switches are expected to be able to support multiple classes of traffic with varying service requirements. This includes traffic classes such as NS/EP traffic, which has guaranteed throughput and bounded delay requirements. Input buffered architectures are being used to deal with memory bandwidth bottlenecks. New challenges exist in switch-matrix and flow-level scheduling as well as in packet classification. Multistage switching fabrics are being revisited and network processors are opening new opportunities for supporting high-level capabilities, including traffic management. In addition, standardization efforts for switch fabric interfaces are ongoing. Overall, this is an exciting time for switch developers and researchers.

Even if vendors could deliver scalable all-optical networks, practical issues may discourage carriers from rolling them out in real life at this time. For instance, there are no standards for carrying management information in optical networks, so carriers may be forced to retain electrical interfaces so they can pinpoint faults.

Presently, with all optical switching networks you get transparency at the expense of manageability. However, standards are being developed to correct this short coming but they are not yet in place. At least three different bodies are working on optical

management specifications: The Optical Internetworking Forum (OIF) (<u>http://www.oiforum.com</u>), which represents 150 companies and led by Cisco Systems, Inc; the Optical Domain Service Interconnect (ODSI) group, which has 50 members, and is being driven by Sycamore Networks, Inc.; and the MPLS working group of the IETF.

Presently, there is no standard for connecting one frequency of blue light to a different frequency of blue light. The only way of avoiding this kinds of issue at present is to buy all transmission and switching equipment from a single vendor. Interoperability will still remain an international issue until standards can be reached and implemented by multiple suppliers.

4.13.1 Wavelength Contention

All-optical switching must contend with a number of issues, the most serious of which is wavelength contention in the overall network. In electro-optical designs, a payload can easily be assigned to a different wavelength when it is converted back to optical form at the output of the switch.

In all-optical designs, the exact same wavelength must be available on both the incoming and outgoing facilities. Otherwise, this can lead to wavelength contention, and traffic engineering can become very difficult as networks grow and/or the number of assigned wavelengths increases to the point where re-assignments become necessary.

To avoid this problem, wavelength translation is performed at the site of the optical switch, either on the switch itself or in adjacent WDM systems. However, there is currently no commercially viable means to perform all-optical wavelength conversions. The workaround is to route a given switch path through loop that performs an OEO wavelength translation.

This solution is cumbersome and uses up switch ports. Also, if the path contains more than one wavelength, the conversion process becomes more complex. Consequently, current practical applications of optical switches leave wavelength assignment and multiplexing to WDM equipment. The all-optical products still have the functional advantage over OEO products of being able to switch the entire contents of a fiber. Hence, while OEO conversion may be eliminated from the switch itself, it is likely that in many cases, there will still be an OEO in the optical path, within the WDM equipment.

Another issue with all-optical networking is where and how traditional maintenance functions, such as monitoring and protection switching, will be accomplished in a pureoptical model. Limited performance monitoring, such as optical signal strength, can be performed by all-optical elements, and restoration and protection switching can be provided for loss-of-signal faults. But monitoring payload bit error rate and coordinating the fault reactions of multiple nodes using path overhead channels is not currently possible without electrically terminating the payload. Some WDM vendors use a side channel to communicate operations, administration and maintenance functions between nodes. The current generation of optical switches, whether OEO or all-optical, are a key component of evolving wavelength-managed optical domain transport. And all-optical switches have the functional advantage of switching the entire contents of a fiber and they are inherently more compact and energy efficient.

4.13.2 Traffic Management and Control

One of the most important and difficult issue associated with the optical network is network management. Among the major concerns are: restoration, performance, and wavelength services. Although network management of optical networks is a topic too large to cover extensively here, some of the important issues are briefly identified and discussed in this section

Foremost, it is important to recognize that optical networks are evolving and being implemented on top of the existing SONET architecture, which already provides its own restoration and protection schemes. Without a highly intelligent network-management system (NMS), it could become very difficult to ensure that restoration schemes between the electrical and optical layers do not conflict with each other. In addition to mediation between the optical and SONET layer, the NMS must be able to prevent possible conflicts or, at the minimum, enable the service provider to identify conflicts.

In addition to managing the overall network, a NMSs must be able to monitor signal performance for each wavelength. With the addition of optical add/drop multiplexers and optical cross-connects, the end-to-end performance of wavelengths becomes more important. A NMS for the optical network must enable carriers to perform troubleshooting of the network by isolating questionable wavelengths and the location of degradation. As the number of wavelengths on each fiber continues to increase, it becomes more important to have an intelligent NMS to monitor them.

4.13.3 Security

Through funding provided in the mid-1990's by the Defense Advanced Research Projects Agency (DARPA), organizations such as the MIT Lincoln Laboratory were able to conducted extensive investigations into the security of all-optical networks and to evaluate and recommend ground-up development of protection strategies against service denial, eavesdropping, traffic analysis and unauthorized access. The goal was to insure that optical networks will have security at a level equal to or greater than in the current generation of electro-optical networks. The work concluded that AON security requirements are fundamentally different from traditional OEO networks. For example, rapid detection is critical for AON because with higher speed communications many bits can be affected in very little time.

Further details on the results of this work may be found via the Internet world wide web at URI: <u>http://www.ll.mit.edu/aon/secureaon.html</u>.

4.13.4 Additional Technology Considerations

The rapid rate of progress in photonic switching has also led to a frantic pace of activity to insure that all requirements are fully supported by evolving systems. These include: congestion management and control, look-up and classification algorithms, multistage switching fabrics, burst switching and other new paradigms, network control issues, interoperability, priority, QoS, restoration, input buffered switch architectures, switchmatrix scheduling, flow-level scheduling, QoS For variable length packets, differentiated services, and multicast support. All of these considerations, when fully deployed, will provide enormous benefits to NS/EP.

5 EMERGING PHOTONIC AND OPTICAL SWITCHING STANDARDS

Today, a number of competing commercial photonic switching solutions are being announced at a very rapid pace. Industry groups are also busy working on their own standards and implementation agreements for photonic switching. Therefore, it is no surprise that the officially recognized national and international standards setting bodies are working at the fastest pace possible to produce the technical specifications necessary to enable interoperability of photonic switching implementations. The ITU-T has defined an architectural model for the "Optical Transport Network" (OTN), which is essentially a more formal designation for the AON.

The ITU-T OTN is an architecture that is already finding its way into commercial products. The ANSI Committee T1 is also playing a very key role in developing standards for this architecture. With conventional optical digital hierarchies, network operators have essentially two degrees of flexibility for transporting services. First, the fiber route provides the means to provide for space diversity. Second, the time slot allocations provide the means for time diversity. Wavelength division multiplexing has provided a new degree of flexibility so that wavelength diversity within a fiber route can be provided.

ITU-T is creating a family of optical networking standards for international use. The expected standards range will be challenging because they cover the network level, functional modeling, equipment and component levels, software, information modeling, hardware, and optical parameters. Standards expertise for these topics within the U.S. are working together on a coordinated strategy basis. ANSI Technical Subcommittee T1X1.5 in particular, is responsible for developing U.S. optical hierarchical interfaces standards and for developing generic functional models for optical networks and optical networking equipment. ANSI has also been making enormous contributions to the ITU work in optical networking. The latest ANSI T1X1.5 information on standards development progress can be found at URI http://www.t1.org/t1x1/x15-hm.htm.

ANSI T1X1 is responsible for digital hierarchy and synchronization standards and has also discussed stand-alone ANSI standards for optical networking. Agreement has been reached that if the ITU makes rapid progress then ANSI standards could then be developed quickly that refine and amplify the choices necessary for North American networks. Using this approach, the effort spent trying to keep parallel standards work by ANSI and ITU in alignment can be refocused on developing the best technical standards.

ANSI T1X1 has been contributing to ITU-T's efforts to develop a standard for messages sent among optical networking equipment. T1X1 has also been working on OTN functional and information models. An ITU-T Recommendation on optical network management has also received contributions from ANSI T1M1. The optics expertise of TIA Working Group FO 2.1.1 has also been solicited to develop specifications for line systems and components. With guidance on network layer issues, TIA FO 2.1.1 will help ITU-T to develop optical networking standards for physical layer aspects along with components and subsystems.

ANSI T1X1 has devoted significant attention to the issues involved in evolving optical networking architectures. All U.S. standards development organizations have been working closely to insure a tight coupling between optical network architectures and physical layer parameters. For example, ANSI T1X1.5 and TIA FO 2.1.1 have been collocating meetings to insure the most collaborative environment possible for the development of network, equipment, and component level standardization. TIA FO 2.1.1 has asked T1X1.5 to develop reference networks to help drive optical parameter choices. T1X1.5 has reference model networks for metropolitan area applications (e.g. a city and its suburbs) and out-state applications (e.g. rural customer to a metropolitan hub). The location and type of equipment interfaces are a key part of these discussions. T1X1.5 is also considering the types of client signals that will travel on the OTN as well as the expected performance requirements for these signals. T1X1.5 has been developing the specific details of how a client signal can be transported "transparently" through an optical network.

The challenges for all of this necessary coordinated standards effort are large. If there is not enough consultation among the various experts groups, it is widely recognized that the initial standards may require corrections to be added later. It is especially recognized that if the standards coordination process is too lengthy the resulting specifications could fall behind the commercial market. There are a host of new physical layer issues to explore, and they are very tightly connected to the size and shape of expected networks.

5.1 ITU-T Recommendation G.709

Titled "Interface for the optical transport network (OTN)" the ink was not even dry on this 2001 year specification before commercial implementations on a chip were being promoted as fully G.709 compliant. The Recommendation defines the interfaces of the Optical Transport Network to be used within and between subnetworks of the optical network, in terms of the Optical Transport Hierarchy (OTH), the functionality of the overhead in support of multi-wavelength optical networks, the frame structures, bit rates, and formats for mapping client signals. The interfaces defined in the recommendation can be applied at the User to Network Interfaces (UNI) and Network Node Interfaces (NNI) of the Optical Transport Network. The specification does not define interfaces that are used within optical subnetworks.

G.709 expands on the definitions contained within ITU-T Recommendation G.872 "Architecture of optical transport networks" by adding new subcategories it further structures the Optical Channel (OCh) by adding new categories of overhead types. It also refines the OCh to operate in either full or reduced functionality (Ochr) and requires the provisioning of transparent network connections between 3R regeneration points. The completely standardized Optical Channel Transport Unit (OTUk) and the functionally standardized Optical Transport Unit (OTUkV) are defined to provide supervision and to condition the signal for transport between 3R regeneration points in the OTN. The OCh substructure provides:

- a. for tandem connection monitoring (ODUkT);
- b. for end-to-end path supervision (ODUkP);
- c. adaption of client signals by means of the Optical Channel Payload Unit (OPUk).

One of the most important features of G.709 is that it improves performance by essentially providing a digital wrapper service that encapsulates the payload with a Reed-Solomon Forward Error Correction (FEC) code. The forward error correction for the OTU-k uses 16 byte interleaved codecs using a Reed-Solomon RS(255,239) code¹¹. The RS(255,239) code is a non-binary code (the FEC algorithm operates on byte symbols) and belongs to the family of systematic linear cyclic block codes. The RS(255,239) is capable of correcting up to 8 errored symbols in a 255 symbol code word (1 symbol = 1 byte in this case). For the FEC processing an OTU row is separated into 16 sub-rows using byte-interleaving. Each FEC encoder/decoder processes one of these sub-rows. The FEC parity check bytes are calculated over the information bytes 1 to 239 of each sub row and transmitted in bytes 240 to 255 of the same sub-row. The bytes in a row belonging to FEC sub-row X are defined by: X+16·(i-1) (for i=1...255).

The generator polynomial for the code is:

$$G(z) = \prod_{i=0}^{15} \left(z - \alpha^i \right)$$

where α is a root of the binary primitive polynomial $x^8 + x^4 + x^3 + x^2 + 1$.

The FEC code word is composed of data bytes and parity and is represented by the polynomial:

$$C(z) = I(z) + R(z)$$

Data are represented by:

$$I(z) = D_{254} \cdot z^{254} + D_{253} \cdot z^{253} + \dots + D_{16} \cdot z^{16}$$

where D_i (*j*=16 to 254) is the data byte represented by an element from *GF*(256) and:

$$D_j = d_{7j} \cdot \alpha^7 + d_{6j} \cdot \alpha^6 + \ldots + d_{1j} \cdot \alpha^1 + d_{0j}$$

The MSB is d_{7j} and d_{0j} is the LSB of the data byte. D_{254} corresponds to byte 1 in the FEC sub-row and D_{16} to byte 239.

Parity bytes are represented by:

$$R(z) = R_{15} \cdot z^{15} + R_{14} \cdot z^{14} + \dots + R_1 \cdot z^1 + R_0$$

Where R_i (j=0 to 15) is the parity byte represented by an element out of GF(256) and

$$R_j = r_{7j} \cdot \alpha^7 + r_{6j} \cdot \alpha^6 + \ldots + r_{1j} \cdot \alpha^1 + r_{0j}$$

where bit r_{7j} is the MSB and r_{0j} the LSB of the parity byte. R_{15} corresponds to the byte 240 in the FEC sub-row and R_0 to byte 255.

R(z) is calculated by

$$R(z) = I(z) \bmod G(z)$$

where "mod" is the modulo calculation over the code generator polynomial G(z) with elements out of the *GF(256)*. Each element in GF(256) is defined by the binary primitive polynomial

$$x^8 + x^4 + x^3 + x^2 + 1$$
.

While commercial implementations do offer full support for the G.709 specified Reed-Solomon based FEC described above, it is also common to find "enhancements" that offer more attractive performance. One commercial implementation, for example, offers an FEC that concatenates two Reed-Solomon codes and is configurable both in error correction capability and block length. This option is useful where the G.709 FEC coding gain is not sufficient. The enhanced FEC algorithm can deliver a coding gain

between zero and 30 percent of overhead. G.709 also specifies that a no FEC option be provided that simply uses fixed stuffed bytes using an all-0's pattern. In addition to the FEC, G.709 specifies that bit scrambling $x^{16}+x^{12}+x^3+x+1$ be performed on the OTUk signal to prevent a long sequence of 1's or 0's.

The ITU-T G.709 standard also specifies an OPUk signal both asynchronous and synchronous modes of mapping at speeds of 2.5 Gb/s, 10 Gb/s, and 40 Gb/s. It is envisioned that the clients of the OPUk will include ATM, IP, and Ethernet.

The frame structure of the ITU-T G.709 wrapper provides for a number of beneficial monitoring points. ODUk path monitoring is supported via explicit fields that provide for: path monitoring, tandem connection monitoring, fault type and fault reporting channel, backward error indication, backward defect indication, and status. The path monitoring overhead is further defined with the following additional subfields: trail trace identifier (TTI), bit interleaved parity (BIP-8), backward defect indication (BDI), and status bits to indicate the presence of a maintenance signal (STAT).

One very interesting, and beneficial attribute of the G.709 wrapper is that it provides for a Trail Trace Identifier (TTI) and an Access Point Identifier. The TTI is a 64 byte string that is structured to contain a 15 character Source Access Point Identifier (SAPI) and a 15 character Destination Access Point Identifier (DAPI). The remaining characters are designated as "operator specific." The Access Point Identifier (API) consists of a 3 character International Segment (IS) and a 12 character National Segment (NS). The IS 3 character is mandated to be based on the 3-character ISO 3166 Country Code (e.g., USA). The NS consists of two sub-fields (1) the ITU Carrier Code (ICC) followed by a Unique Access Point Code (UAPC). The ICC is encoded in accordance with ITU-T M.1400. The UAPC is a matter for the organization to which the country code and ITU carrier code have been assigned. Thus G.709 provides a unique NS of 6-11 characters that are followed by a trailing NUL to complete the 12 character segment. Within the USA the assignment of the NS would fall under the auspices of the US State Department unless otherwise delegated.

The G.709 wrapper also provides another interesting and potentially useful protocol fields. The standard sets aside two bytes of ODUk overhead for "Experimental" (EXP) purposes to a vendor and/or a network operator for use within their own subnetwork to support an application that requires additional ODUk overhead. Since the standard specified that there is no requirement to forward the EXP overhead beyond the private subnetwork, any application usage would be confined to the private subnetwork.

One of the primary benefits of the G.709 wrapper is that it transparently adds an error correction mechanism and reserves a number of protocol bytes for future standardization work. The dB coding gain provided by the G.709 wrapper should prove especially useful to maximize the performance of ultra long haul links, and to allow the use of cost optimized optical solutions in metropolitan networks. The G.709 Recommendation provides a significant step forward in the direction toward a standards based OTN.

If there is one very glaring piece missing from the expected flexible OTN architecture at this point it is that it does not have any explicit association with a control layer.

5.2 ITU-T Recommendation G.872

One of the other major accomplishments by the ITU-T to date in the effort to standardize the OTN has been the adoption of ITU-T Recommendation G.872 titled "Architecture of optical transport networks." This Recommendation lays out a fundamentally functional architecture for constructing optical transport networks. The OTN functionality is described from a network level viewpoint, taking into account an optical network layered structure, client characteristic information, client/server layer associations, networking topology, layer network functionality providing optical signal transmission, multiplexing, routing, supervision, performance assessment, and network survivability. Analog or mixed digital/analog signals are excluded from the scope of G.872.

G.872 provides the functional architecture necessary for an OTN that supports the transport of digital client signals. ITU-T G.872 also specifies that an OTN is "a transport network bounded by optical channel access points". The ITU-T G.872 OTN architecture is based on a layered structure, which includes:

- a. an optical channel layer network (designated as OCh);
- b. an optical multiplex layer network, (designated as OMS);
- c. an optical transmission layer network (designated as OTS).

The OCh is intended to support the requirements for end-to-end networking of optical channel trails between access points. The functionality that has been assigned to the OCh includes: routing, monitoring, grooming, and protection and restoration of optical channels. In this arrangement, programmable optical crossconnects, with rearrangeable switch fabrics and intelligent control planes, will be critical to the realization of the OCh layer functions, especially in mesh optical networks

The OCh layer network is responsible for supporting the following functions:

- a. optical channel connection rearrangements to support flexible network routing;
- b. optical channel overhead processes that ensure the integrity of the optical channel adapted information;
- c. optical channel supervisory functions for enabling network level operations and management functions including network flexibility and service quality.

The OMS layer network provides the functionality for networking of a multi-wavelength optical signal. A "multi-wavelength" signal is defined to include the case of just one optical channel.

The functions assigned to the OMS layer network includes:

- a. optical multiplex section overhead processes for ensuring integrity of the multi-wavelength;
- b. optical multiplex section adapted information;
- c. optical multiplex section supervisory functions for enabling section level operations;
- d. management functions such as multiplex section survivability.

The OTS layer network functions include:

- a. optical transmission overhead processing to ensure the integrity of optical transmission section adapted information;
- b. optical transmission supervisory functions to render support for operating operations;
- c. management functions such as transmission section survivability.

ITU-T G.872 also mentions a physical media layer network that is defined as an optical network that is the server of optical transmission. This physical media layer network was not included within the scope of G.872.

5.2.1 Interconnection and Interworking Between Different Administrative Domains

As optical networking technology is evolving, so will the methods by which interconnection and interworking between different carrier networks takes place. In this context, interconnection is used to describe a physical interface between two carrier networks. Interworking refers to the agreed networking level between carriers and is described in terms of the characteristic information that is transferred transparently across networks. G.872 describes three scenarios:

a) OTN islands within carrier networks that are initially WDM point-to-point line systems and more complex optical network elements are introduced; interconnection among existing carrier transport networks may take place at one of the physical interfaces, which have been standardized, for these networks. Such interconnection generally involves modifying the physical characteristics of the signal, which is passed over an inter-domain interface, such as a G.957, "Optical interfaces for equipments and systems relating to the synchronous digital hierarchy," so that the adapted information of the signal is OTN compliant.

- b) In the second scenario OTN compliant systems will be applied to interconnect carrier networks.
- c) Last, after the standards for the overhead are in place and implemented, it will become possible to provide continuity for the OCh at the interconnection point between different carrier networks.

Based on scenarios described above it is clear that the ITU will not create intra-domain interfaces. For organizations that are able to purchase all networking equipment from a single supplier this approach is satisfactory. However, where it is not possible for an organization to deploy a single vendor OTN, the interoperability will be limited to that used via an inter-domain connection.

5.2.2 Transport Functional Architecture of Optical Networks

Optical transport networks are comprised of functionality providing transport, multiplexing, routing, supervision and survivability of client signals that are processed principally in the photonic realm. G.872 specifically addresses the aspects concerning the optical transport network layered structure, characteristic information, client/server layer associations, network topology, and layer network functionality.

In Recommendation G.805, "Generic functional architecture of transport networks," the optical transport network is decomposed into independent transport layer networks such that each layer network can be separately partitioned in a way that reflects the internal structure of that layer network.

5.3 ITU-T Recommendation E.106 Description of an International Emergency Preference Scheme (IEPS)

Established on March 17, 2000 this ITU-T Recommendation began a standardization process for supporting requirements such as those of an international emergency team that may need emergency coordination of efforts to be facilitated on a multi-national basis. A number of the features described for use within the IEPS are very similar to those found in the United States Government Emergency Telecommunications Service (GETS) designed to support the requirements of the OMNCS.

Section six of the ITU-T specification states that "Calls from IEPS users should be suitably marked at the network entrance and such markings should be associated with the call to completion (i.e. IEPS calls should be marked from end to end)." The clear advantages associated with this capability are, regretfully, diluted within the same section in Note 2, which states: "The call marking, marking interpretation and the processing arrangements will have to be specified and fully agreed at the gateway points. Specific

arrangements to transfer the marked signals would also need to be agreed with nonparticipating but intermediate transit countries." Regretfully, this ambiguity will result in higher than necessary short term system costs even where the parties involved are in agreement.

E.106 also specifies a number of essential network including: priority dial tone, priority call setup, including priority queuing schemes and exemption from restrictive management controls such as call gapping. Additional language states: "A specific identifying mark is associated with the call which prompts operational elements of the public switched network to provide advantages in signaling, switching and traffic routing over non-marked calls features"

This standard is clearly a step in the right direction toward the production of national and international level standards that can support the recoganized traffic prioritization mechanisms needed during times of national disaster crisis such as NS/EP events. Objectively, however, it should be noted that this version of E.106 provides language that outlines what functional requirements should be supported. The Recommendation does not actually specify any standardized bit encodings, processing algorithms, or any other mechanisms that would be helpful to accomplish the E.106 requirements in an internationally standardized manner. While it appears that much work remains to be done in order to progress the international standardization necessary to support NS/EP event requirements, at least E.106 is a good beginning.

A new ITU-T Study Group 16, Multimedia Services, Recommendation F.706 titled: International Emergency Multimedia Service (IEMS) has completed. F.706 is an extension to E.106. IEMS addresses IP-telephony and multimedia Internet applications such as SMTP, instant messaging, and multicast over IP-base networks. Study Group 16 is also working to establish a priority mechanism in the ITU-T H.323 titled: "Packetbased multimedia communications systems," call control protocol, to establish a quality of service class for emergency communications, and to address the security issues for authentication and protection. It should be noted that the ITU-T work is being carried over into the Internet in several ways. For example, an Internet draft was published with an expiration date of August 20, 2001, which essentially provides a copy of the ITU-T 106 Recommendation to the Internet community. The Internet draft also attempts to promote the goals expressed by E.106 by (1) the Internet draft offers the opportunity to join a mailing list dedicated to discussion of IEPS issues (ieps@listserv.gsfc.nasa.gov), and (2) the Internet draft also references a web site devoted to progressing IEPS related matters http://www.iepscheme.net. These additional reference sources promoted within the draft Internet RFC are invaluable sources for additional information and participation.

Access to E.106 IEPS encodings at the G.709 API would facilitate monitoring and control operations at the photonic switching level based on IEPS requirements.
5.4 ANSI T1X1.5

Originally, the goal of ANSI T1X1.5, and other standards organizations, was clearly understood to be the development of a transparent optical network. ANSI T1X1.5 was responsible for making significant contributions to the work of the ITU-T in the development of practical standards. ITU-T G.709 has, for all practical purposes, placed optical transparency on the shelf in favor of moving forward to enable compelling network requirements such as Quality of Service measurements to be made.

5.4.1 Transparency

Optical Transport Network standards work in ITU-T and T1X1 began with a goal of transporting any optical digital signal without limits on the signal format, and with no minimum or maximum limits on the bit rate. This goal was believed to offer the greatest value to network operators in terms of flexibility. The OTN design was required to accommodate established SONET and gigabit Ethernet signals with a minimum of time and cost.

The concept of bit rate and format transparency was sometimes extended to include optical transparency (i.e. once a single channel optical signal has been created, keep it optical until it is terminated). As previously described, avoiding OEO transitions reduces costs. Thus the initial goals for the OTN design, especially in terms of transparency, were very high.

5.4.2 Limits

Two current technology limits place constraints on what can be practically accomplished in the short term by standards organizations seeking to provide optically transparent networks. These are (1) frequency domain performance measurements and (2) 3R regeneration.

5.4.3 Frequency Domain Performance Measurements

The first limit is the inability of optical frequency-domain measurements to predict client signal performance such as the bit error ratio to the accuracy achieved by PDH or SONET/SDH technologies. Accurate performance management data has been deemed a very desirable network feature.

ITU-T and ANSI T1X1 have reacted favorably to proposals for "digital wrappers" to be added to each client signal by the adoption of G.709. The optical signal is converted to electronic, digitally increased in bit rate to provide overhead bandwidth, and converted back to an optical signal. This allows accurate performance management data without ties to the client signal format. Another benefit is the use of forward error correction. The price to pay to enter the OTN with accurate performance management data is the loss of optical transparency.

5.4.4 3R Regeneration

Optical channels accumulate impairments when traveling through multiple stages of gain, loss, multiplexing, and routing. For long haul applications, this is overcome by deploying 3R regeneration. A second technology limit is that current 3R regenerators employ OEO conversions. Again, this renders the loss of optical transparency for long haul applications.

More importantly, current 3R regenerators restrict bit rate transparency to one rate, or at best a set of discrete bit rates. It is therefore cost prohibitive to deploy 3R regenerators for every imaginable bit rate within a long haul network.

The G.709 Recommendation adopted by ITU-T to restrict standardized OTN signals to a set of three discrete bit rates. Once again the price to pay to enter the OTN is the loss of bit rate transparency.

5.5 Internet Engineering Task Force (IETF)

As identified in section three of this report, the Internet has been and continues to be the most rapid growth area within the telecommunications industry. Consequently, it is not surprising that the IETF has been very active recently in the development of specifications to enable Internet TCP/IP applications to take advantage of the evolving OTN. Internet market forces have played such a key role in changing the traditional circuit switched modes of carrier networks that any serious consideration of photonic switching or the evolving OTN must include the IETF work.

5.5.1 MPLS and GMPLS Extensions

In January 2001 the IETF published RFC 3031 "Multiprotocol Label Switching (MPLS) as a "Standards Track" document. The IETF work is expected to evolve MPLS into a set of specifications that together can be used to building an operational MPLS system. Astonishingly, in a very short period of time the IETF has published and/or has received approximately 100 draft proposals related to MPLS so clearly this is a very active area of standardization within the Internet community and it is quite likely that a number of these proposals will be adopted and published.

MPLS separates the control plane from the data plane. MPLS specifications can already be applied to both routers and ATM switches, and draft specifications to add MPLS support for optical cross-connects (OXC) is already under way. In addition to MPLS there is also a draft specification titled: "Generalized MPLS" or GMPLS. The purpose of GMPLS is to extend MPLS to support time-division (e.g. SONET ADMs), wavelength (optical lambdas), and spatial switching (e.g. incoming port or fiber to outgoing port or fiber). The GMPLS specification extends the control plane beyond routers and ATM switches all the way down to physical layer devices including SONET ADMs, optical switches and legacy TDM devices. GMPLS employs Intermediate System (IS) to Intermediate System (IS) routing. Since there are a number of MPLS implementations already available in the marketplace it may prove to be simpler to add the GMPLS extensions into an updated version of the MPLS specification but this would be a decision to be made by the IETF.

For Internet Protocol based networks MPLS brings benefits that include:

- (a) Traffic Engineering so that it is possible to establish the path that IP traffic will take through the network, and the ability to set performance characteristics for a class of traffic.
- (b) Virtual Private Networks (VPN) can be created by service providers using MPLS to create IP tunnels throughout their network, without the need for end user based encryption services.
- (c) Providing traffic with different qualitative Classes of Service (CoS) and with different quantitative Quality of Service (QoS)
- (d) providing IP based Virtual Private Networks (VPN's).

One of the most important benefits that MPLS offers is the opportunity to eliminate multiple layers. For example, for IP networks some carriers employ an overlay model where ATM is used at Layer 2 and IP is used at Layer 3. MPLS provides the capability to move many of the functions of the ATM control plane to layer 3. This can greatly simplify network management and protocol complexity.

MPLS describes an approach to the design of control planes for optical cross connects (OXCs), which leverages existing control plane techniques developed for MPLS Traffic Engineering. The proposed approach combines recent advances in MPLS traffic engineering control plane constructs with OXC technology to:

- (a) provide a framework for real-time provisioning of optical channels in automatically switched optical networks;
- (b) foster the expedited development and deployment of a new class of versatile OXCs;
- (c) allow the use of uniform semantics for network management and operations control in hybrid networks consisting of OXCs and label switching routers (LSRs). The proposed approach is particularly advantageous for OXCs intended for data-centric optical internetworking systems. In such environments, it will help to simplify network administration. This approach also paves the way for the eventual incorporation of DWDM multiplexing capabilities in IP routers.

In an MPLS network, incoming packets are assigned a "label" by a "label edge router (LER)". Packets are forwarded along a "label switch path (LSP)" where each "label

switch router (LSR)" makes forwarding decisions based solely on the contents of the label. At each hop, the LSR strips off the existing label and applies a new label which tells the next hop how to forward the packet.

Label Switch Paths (LSPs) are established by network operators for a variety of purposes, such as to guarantee a certain level of performance, to route around network congestion, or to create IP tunnels for network-based virtual private networks. In many ways, LSPs are no different than circuit-switched paths in ATM or Frame Relay networks, except that they are not dependent on a particular Layer 2 technology.

An LSP can be established that crosses multiple Layer 2 transports such as ATM, Frame Relay or Ethernet. Thus, one of the true promises of MPLS is the ability to create end-toend circuits, with specific performance characteristics, across any type of transport medium, eliminating the need for overlay networks or Layer 2 only control mechanisms.

A result of these trends, therefore, is the evolution of optical transport networks from simple linear and ring topologies to mesh topologies. By a mesh (not necessarily fully meshed) topology, we mean a connected (not necessarily fully connected) network of arbitrary topology in which the node degree is typically more than two. In mesh optical networks, optical crossconnects engender versatility and reconfigurability by performing switching and rearrangement functions.

5.6 RFC 2702 "Requirements for Traffic Engineering Over MPLS"

RFC 2702 was published in September 1999 as an informational RFC to the Internet community. The RFC is of special interest for NS/EP purposes because it identifies the needs, within the context of Internet Protocol based networks, for an optional "preemption attribute" that can be used to specify four preempt modes for a traffic trunk. RFC 2702 also clarifies that preemption can also be used to implement various prioritized restoration policies following fault events. As outlined in the RFC the preemption attribute can be encoded to specify four preempt modes for a traffic trunk:

- a. preemptor enabled;
- b. non-preemptor;
- c. preemptable;
- d. non-preemptable.

The RFC 2702 preemption attribute is intended for use to determine whether a traffic trunk can preempt another traffic trunk from a given path, and whether another traffic trunk can preempt a specific traffic trunk. The intended purpose of the preemption attributed was for use in achieving traffic oriented and resource oriented performance objectives. The RFC also identifies requirements where preemption can be used to assure favorable routing paths for high priority traffic even in a differentiated services environment.

The important benefit derived from the technical characteristics associated with a preemptor enabled traffic trunk is that it can preempt lower priority traffic trunks designated as preemptable. This capability, for example, would allow the preemption of routine traffic so that traffic supporting an NS/EP event (e.g., medical or evaluation traffic associated with a natural disaster). In accordance with the RFC, a traffic trunk that is specified as non-preemptable cannot be preempted by any other trunks, regardless of the relative priorities. A traffic trunk designated as preemptable can be preempted by higher priority trunks which are preemptor enabled. The RFC defines some preempt modes to be mutually exclusive. For example, a particular trunk "x" can preempt another traffic trunk "y" only if all of the five conditions are true:

- a. *x* is a higher priority than *y*;
- b. *x* requests a resource in use by *y*;
- c. concurrent use of *x* and *y* are prohibited by operational parameters;
- d. x is configured as preemptor enabled;
- e. *y* is configured to accept preemption.

In accordance with the current industry standard Internet "best effort" service model preemption is not a mandatory attribute but the publication of this RFC can be viewed as a step forward in recognizing the usefulness of preemption. The usefulness of preemption is much more compelling in a differentiated services scenario. Furthermore, to reduce costs some of the evolving optical internetworking architectures move some protection and restoration functions from the optical layer to data network elements (e.g., gigabit and terabit label switching routers). Under fault conditions the restoration time for high priority traffic trunks can be significantly reduced through the use of preemption techniques.

While solutions other than preemption have been proven to satisfy NS/EP requirements in environments such as the Government Emergency Telecommunications Service (GETS), RFC 2702 is important because it identifies preemption as a solution for supporting GETS type traffic over Internet Protocol based networks. For additional information visit <u>http://iepscheme.net</u>.

5.6.1 Optical Interworking Forum (OIF)

The OIF is an industry-wide initiative to create open forum focused on accelerating the deployment of optical internetworks. The goal of the OIF is to provide a venue for equipment manufacturers, users and service providers to work together to resolve issues and develop key specifications to ensure the interoperability of optical networks.

The OIF is focused on addressing optical internetworking issues. Optical internetworks are data networks that natively access an underlying optical transport network. Data networks are composed of various technologies such as ATM and IP routers/switches; optical transport networks include WDM terminals, optical amplifiers or even the fiber itself. Optical internetworking is not concerned with the issues within the data or optical

network; instead, it addresses the interoperability between the data and the optical network. For example, optical internetworking would not require the ATM connection routing protocols to change because that is a function defined within the data network. Optical internetworking shares information between the optical network and various data networking layers. The information passed between the layers define the functions supported by the adjacent network.

Technology progress has enabled advancements in speed of service and previously unimagined capabilities and as different service providers have different objectives, there are more choices than ever before regarding how data networks are architected. Circuit switched voice networks were built on a time division multiplexed digital hierarchy. In this architecture, voice channels operating at 64Kbps are repeatedly aggregated into higher bit rate signals until reaching fiber rates, as defined by SONET/SDH rates. All traffic passed through the SONET/SDH layer. This is no longer necessarily the case. Data networks based on packets/cells support protocol multiplexing and have the ability to access bandwidth in many new combinations. For example, ATM and IP networks can directly access the optical network, bypassing SONET/SDH. Thus, there are multiple protocol reference models that can be used to describe optical internetworks.

5.7 Standards Conclusions

The marketplace is currently offering a diverse set of photonic switching technology alternatives including: MEMS, Bubble Switching, and other technologies. Additionally, the future promises offered by the incorporation of photonic crystals and an increasing use of quantum mechanics based solutions suggest a bright evolutionary future for this area of technology application and standardization. Mostly, the internals of today's photonic switching systems are built using proprietary architectures but all do provide support for interconnecting to a select set of prevailing technologies including: SONET, IP, Fibre Channel, Gigabit Ethernet, DWDM, IP, and ATM. Many of the systems also provided an Application Program Interfaces (API) to either IETF Simple Network Management Protocol (SNMP), ITU-T Common Management Information Protocol (CMIP), or proprietary management systems. Some systems support the Object Management Group (OMG) Common Object Request Broker Architecture (CORBA) and systems also contain embedded routing and signaling support that is based on the IETF GMPLS or MPLS standards for connection management and IP services integration. Leading industry vendors are promoting their ability to support single wavelength switching capacity of up to 40 Tb/s. Today's photonic switching systems, however, can support single and multi-wavelength applications with operating windows of 1200 – 1620 nanometers. Increasingly, other standards including HTML/XML and CORBA object interfaces are being used to control the photonic switching process and this is a positive step in the breadth of standardization employed.

National and international standards organizations are aggressively working to develop an OTN/AON architecture to support and promote interoperability, reliability, and common management among carrier services providers. It is clear that both ANSI and the ITU-T are both keenly aware of the importance of providing timely specifications that can be readily adopted before vendors adopt their own solutions. The IETF presence is also providing an important stimulant with regards to the rapid development of practical solutions to meet the new technical challenges posed by photonic switching and the move toward OTN/AON.

6 CONCLUSIONS AND RECOMMENDATIONS

Photonic switching is a rapidly evolving and highly competitive area of technology that is experiencing a substantial level of financial investment by both the private sector and by U.S. government research funding agencies such as DARPA. In particular the growth of the Internet has been responsible for changing the nature of the existing telecommunications infrastructure from a circuit-switching environment to a packet switching environment. Additionally, customer demand for telecommunications bandwidth and advanced services such as dynamically reconfigurably networks is passing from being optional to a mandatory requirement. At this point, it is not entirely clear how the rapidly changing revenue aspects associated with a large scale shift from voice to data dominance will be incorporated into provider pricing strategies. We can only say at this point that, from a switching perspective, a packetized infrastructure should be much less costly to implement than an equivalent circuit-switch system.

The quantum mechanics and other theoretical work completed in the early part of the 20th century is not only becoming demonstrable in the laboratory but in cases such as quantum wells, are now being utilized in common inexpensive circuitry. The most fundamentally promising area of future photonic switching component building blocks, photonic crystals, is an area that is rapidly yielding and entirely new era of miniaturization, speed, and cost reductions. Three dimensional crystal lattice structures hold promising advancements in band gap engineering. Other advancing areas such as nanostructures also offer to substantial advances in miniaturization. Indeed, the famous speech given by Richard Feynman on December 29, 1959 at the annual meeting of the American Physical Society at the California Institute of Technology (Caltech) titled " There's Plenty of Room at the Bottom" is becoming more true at an ever increasing rate.

A wide range of organizations are attempting to address the needs for optical standardization, interoperability, and management of photonic networks. Now that the ITU-T G.709 recommendation has been adopted internationally, the Department of State is responsible for the assignment of the NS UAPC encodings within the U.S.; unless otherwise delegated. It is, therefore, recommended that the OMNCS further evaluate the use of the 6-11 character field of the G.709 UAPC for the specific NS/EP support purposes that it offers. Additionally, it is recommended that the OMNCS further evaluate the use of the ITU-T G.709 2 byte ODUk overhead EXP code assignments within the context of specific NS/EP subnetworks. Operational use and evaluation should not require the NCS to coordinate with service providers or external agencies because of the manner in which G.709 has specified use of the field. The OMNCS should be free to choose NS/EP specific encodings and associated actions based on this field. The OMNCS should be free to monitoring and controlling operations at the photonic switching level based on IEPS requirements.

It is also recommended that the OMNCS should actively monitor and, to the extent feasible, participate in the rapidly evolving OTN standards via ANSI T1X1.5 and other recognized standards bodies. Positive cooperation between the OMNCS and the

Department of State is critical to insuring that the requirements within the deregulated environment prevalent in the United States are considered on an equal basis with other countries that may still be dominated by a heavily regulated telecommunications environment.

It is recommended that the OMNCS further evaluate the potential NS/EP benefit offered by choosing photonic switching product implementations that incorporate the Internet RFC 2702 "MPLS Traffic Engineering" optional preemption support attribute. The goal of RFC 2707 specification is to assure that high priority traffic trunks can always be routed through relatively favorable paths within a differentiated services environment. This appears to be very consistent with OMNCS NS/EP goals.

For NS/EP purposes, at least in the short term, it appears that modest sized photonic switching solutions that package ITU-T G.709 functionality along with IETF MPLS will offer the greatest initial benefits, where the cost savings offered are warranted.

Appendix A: Acronyms

AGVD	Anomalous Group-Velocity Dispersion
ANSI	American National Standards Institute
AON	All Optical Networks
API	Access Point Identifier
API	Application Program Interfaces
BEC	Boise-Einstein Condensate
BER	Bit Error Ratio
BDI	Backward Defect Indication
BIP-8	Bit Interleaved Parity
BIT	Binary Digit
Caltech	California Institute of Technology
CORBA	Common Object Request Broker Architecture
CoS	Classes of Service
CMIP	Common Management Information Protocol
DAPI	Destination Access Point Identifier
DARPA	Defense Advanced Research Projects Agency
dB	decibels
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium-doped Fiber Amplifier
E.O.	Executive Order
EOP	Executive Office of the President
eV	electron volt
EXP	Experimental
FCC	Federal Communications Commission
FEC	Forward Error Correction
GETS	Government Emergency Telecommunications Service
GHZ	Greenberger-Horne-Zeilinger
HPC	High Probability of Completion
ICC	ITU Carrier Code
IEMS	International Emergency Multimedia Service
IEPS	International Emergency Preference Scheme
IETF	Internet Engineering Task Force
IOC	Integrated Optical Circuit
IOCs	Integrated Optical Circuits

IS	International Segment
ITU	International Telecommunications Union
ITU-T	International Telecommunications Union - Telecommunication
	Standardization Sector
LCD	Liquid Crystal Display
LER	Label Edge Router
LSP	Label Switch Path
LSPs	Label Switch Paths
LSR	Label Switch Router
LSRs	Label Switching Routers
	C
Mb/s	megabytes per second
MEMS	Micro Electro-Mechanical Systems
MPLS	Multiprotocol Label Switching
MIT	Massachusetts Institute of Technology
N6	Technology and Standards Division
NCS	National Communications System
NMS	Network-Management System
NNI	Network Node Interfaces
NS/EP	National Security/Emergency Preparedness
NS	National Segment
PDL	Polarization Dependent Loss
PXC	Photonic Cross-Connects
OC-1	Optical Carrier Level 1
OCh	Optical Channel
Ochr	Optical Channel Rreduced
ODSI	Optical Domain Service Interconnect
ODUkP	End-to-End Path Supervision
ODUkT	Tandem Connection Monitoring
O-E-O	Optical-Electrical-Optical
OEO	Optical-Electrical-Optical
OIF	Optical Internetworking Forum
OMG	Object Management Group
OMNCS	Office of the Manager, NCS
OPUk	Optical Channel Payload Unit
OTH	Optical Transport Hierarchy
OTN	Optical Transport Network
OTUk	Optical Channel Transport Unit
OTUkV	Optical Transport Unit
OXC	Optical Cross-Connect
OXCs	Optical Cross-Connects

QoS	Quality of Service
QUBIT	Quantum Bit
RFC	Request For Comment
SAPI	Source Access Point Identifier
S/N	Signal-to-Noise Ratio
SNMP	Simple Network Management Protocol
SPI-4	System Physical Interface Level 4
SPM	Self-Phase Modulation
SS7	Signaling System No. 7
STAT	Maintenance Signal
STS-1	Synchronous Transport Signal 1
Tb/s	terabytes per second
TTI	Trail Trace Identifier
UAPC	Unique Access Point Code
UNI	User to Network Interfaces
VPN	Virtual Private Network
VPN's	Virtual Private Networks
VSR	Very Short Reach
	-

Appendix B: References

- 1. "Photonic Devices for Telecommunications," Guekos, G., Springer-Verlag Berlin 1999. ISBN 3-540-64318-4.
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Appendix C: Standards References

- 1. ITU-T Recommendation G.805 (1995), "Generic functional architecture of transport networks."
- 2. ITU-T Recommendation G.681 (1996), "Functional characteristics of interoffice and long-haul line systems using optical amplifiers, including optical multiplexing."
- 3. ITU-T Recommendation G.709 (Feb 2001) "Interface for the optical transport network (OTN)."
- 4. ITU-T Recommendation E.106 (Mar 2000) "Description of an International Emergency Preference Scheme (IEPS).
- 5. Recommendation F.706 titled: International Emergency Multimedia Service (IEMS).
- 6. American National Standard T1.523-2001 "Telecom Glossary 2000."
- 7. ITU-T Recommendation G.872 (1999) "Architecture of optical transport networks."
- 8. ITU-T Recommendation G.957 (1999) "Optical interfaces for equipments and systems relating to the synchronous digital hierarchy."
- 9. ITU-T Recommendation H.323, (2000) "Packet-based multimedia communications systems."
- 10. IETF RFC 3031 (2001) "Multiprotocol Label Switching (MPLS)."
- 11. IETF RFC 2702 (1999) "Requirements for Traffic Engineering Over MPLS."

Appendix D: OIF Specifications

To date the Optical Interworking Forum has produced the following interworking specifications:

- SPI-4 phase 1 (OC-192 System Packet Interface) OIF-SPI4-01.0 System Physical Interface Level 4 (SPI-4) Phase 1: A System Interface for Interconnection Between Physical and Link Layer, or Peer-to-Peer Entities Operating at an OC-192 Rate (10 Gb/s).
- SPI-4 phase 2 (OC-192 System Packet Interface) OIF-SPI4-02.0 System Packet Interface Level 4 (SPI-4) Phase 2: OC-192 System Interface for Physical and Link Layer Devices.
- 3. VSR-1 (OC-192 Very Short Reach Interface, 12 fiber 850nm) OIF-VSR4-01.0 Very Short Reach (VSR) OC-192 Interface for Parallel Optics.
- 4. VSR-2 (OC-192 Very Short Reach Interface, 1 fiber 1310nm) OIF-VSR4-02.0 -Serial OC-192 1310nm Very Short Reach (VSR) Interfaces.
- 5. VSR-3 (OC-192 Very Short Reach Interface, 4 fiber 850nm) OIF-VSR4-03.0 Very Short Reach (VSR) OC-192 Four Fiber Interface Based on Parallel Optics
- 6. VSR-4 (OC-192 Very Short Reach Interface, 1 fiber 850nm) OIF-VSR4-04.0 Serial Shortwave Very Short Reach (VSR) OC-192 Interface for Multimode Fiber

Appendix E: Photonic Switching Terms

Selected Photonic Switching terms from T1.5-2001 American National Standard for Telecommunications - Telecommunications Glossary 2000

- 1. photonic switching: The use of photonic devices rather than electronic devices to make or break connections within integrated circuits.
- 2. photonics: The science of generating and harnessing light as well as other forms of radiant energy whose quantum unit is the photon.
- 3. photoconductivity: In certain materials, the increase in electrical conductivity that results from increases in the number of free carriers generated when photons are absorbed. Note: The photons must have quantum energy sufficient to overcome the band-gap in the material in question.
- 4. photon: A discrete packet, i.e., quantum, of electromagnetic energy. Note: The energy of a photon is h, where h is Planck's constant and is the frequency of the electromagnetic wave.
- 5. Planck's constant: The constant of proportionality, represented by the symbol h, that relates the energy E of a photon with the frequency of the associated wave through the relation E = h, where $h = 6.626 \times 10^{-34}$ joule•second.
- 6. photoconductivity: In certain materials, the increase in electrical conductivity that results from increases in the number of free carriers generated when photons are absorbed. Note: The photons must have quantum energy sufficient to overcome the band-gap in the material in question.
- 7. photodiode: A semiconductor diode that produces, as a result of the absorption of photons, (a) a photo voltage or (b) free carriers that support the conduction of photocurrent. Note: Photodiodes are used for the detection of optical communication signals and for the conversion of optical power to electrical power.
- 8. quantum efficiency: In an optical source or detector, the ratio of the number of output quanta to the number of input quanta. Note: Input and output quanta need not both be photons.
- 9. quality of service (QOS): 1. The performance specification of a communications channel or system. Note: QOS may be quantitatively indicated by channel or system performance parameters, such as signal-to-noise ratio (S/N), bit error ratio (BER), message throughput rate, and call blocking probability. 2. A subjective

rating of telephone communications quality in which listeners judge transmissions by qualifiers, such as excellent, good, fair, poor, or unsatisfactory.

- 10. quantum noise: Noise attributable to the discrete and probabilistic nature of physical phenomena and their interactions. Note 1: Quantum noise represents the fundamental limit of the achievable signal-to-noise ratio of an optical communication system. This limit is never achieved in practice. [After FAA] Note 2: Examples of quantum noise are photon noise in an optical signal and shot noise in an electrical conductor or semiconductor.
- 11. shot noise: The noise caused by random fluctuations in the motion of charge carriers in a conductor. Note: There is often a minor inconsistency in referring to shot noise in an optical system: many authors refer to shot noise loosely when speaking of the mean square shot noise current (amperes2) rather than noise power (watts).
- 12. optical fiber: A filament of transparent dielectric material, usually glass or plastic, and usually circular in cross section, that guides light. Note 1: An optical fiber usually has a cylindrical core surrounded by, and in intimate contact with, a cladding of similar geometry. Note 2: The refractive index of the core must be slightly higher than that of the cladding for the light to be guided by the fiber. Synonym lightguide.
- 13. OC: Abbreviation for optical carrier. The nomenclature for the line rate of the optical transmission signal. [T1.106-1988]
- 14. open waveguide: An all-dielectric waveguide in which electromagnetic waves are guided by a refractive index gradient so that the waves are confined to the guide by refraction or reflection from the outer surface of the guide or from surfaces within the guide. Note 1: In an open waveguide, the electromagnetic waves propagate, without radiation, within the waveguide, although evanescent waves coupled to internal waves may travel in the space immediately outside the waveguide. Note 2: Examples of open waveguides are (a) optical fibers and (b) planar waveguides in integrated optical circuits. [From Weik '89]
- 15. optical carrier level 1 (OC-1): The optical signal that results from an optical conversion of a synchronous transport signal 1 (STS-1 signal). It is this signal that will form the basis of the interface. [T1.105-1988]
- 16. beamsplitter: A device for dividing an optical beam into two or more separate beams. Note: An example of a beamsplitter is a partially reflecting mirror.
- 17. fiber amplifier: A device that amplifies an optical signal directly, without the need to convert it to an electrical signal, amplify it electrically, and reconvert it to an optical signal. Note 1: One type of fiber amplifier uses a doped fiber (e.g., a fiber doped with erbium), which bears the communication signal, and which is

optically pumped with a laser having a high-powered continuous output at an optical frequency slightly higher than that of the communication signal. The signal is intensified by Raman amplification. Note 2: Because neither opticalelectrical conversion nor electrical amplification takes place, this type of amplifier is well suited for a wide variety of applications, both digital and analog. Note 3: Because this type of amplifier does not require extraordinary frequency (wavelength) control of the pumping laser, it is relatively simple. Synonym Raman amplifier.

- 18. optical cavity: A region bounded by two or more mirrors that are aligned to provide multiple reflections of lightwaves. Note: The resonator in a laser is an optical cavity. In this sense, synonym resonant cavity.
- 19. optical fiber nuclear hardening: Design allowances made to prevent or ameliorate the effects of gamma or high-energy neutron radiation or bombardment, that causes some optical fibers to darken, increase attenuation, or depart from normal operating parameters. Note: Light sources, such as LEDs and lasers, and photodetectors, also need to be hardened to prevent similar malfunctions. [From Weik '89]
- 20. optical switch: A switch that enables signals in optical fibers or integrated optical circuits (IOCs) to be selectively switched from one circuit to another. Note 1: An optical switch may operate by (a) mechanical means such as physically shifting an optical fiber to drive one or more alternative fibers, or (b) electro-optic effects, magneto-optic effects, or other methods. Note 2: Slow optical switches, such as those using moving fibers, may be used for alternate routing of an optical transmission path, e.g., routing around a fault. Fast optical switches, such as those using electro-optic or magneto-optic effects, may be used to perform logic operations.
- 21. optical waveguide: Any structure having the ability to guide optical energy. Note: Optical waveguides may be (a) thin-film deposits used in integrated optical circuits (IOCs) or (b) optical fibers.
- 22. opto-electronic: Pertaining to any device that functions as an electrical-to-optical or optical-to-electrical transducer, or an instrument that uses such a device in its operation. Note 1: Photodiodes, LEDs, injection laser diodes, and integrated optical circuit (IOC) elements are examples of opto-electronic devices commonly used in optical fiber communications. Note 2: "Electro-optical" is often erroneously used as a synonym.

Appendix F: Web Sites

- 1. American National Standards Institute T1X1.5 Homepage http://www.t1.org/t1x1/_x15-hm
- 2. International Telecommunications Union (ITU) G -series transmission systems and media, digital systems and networks. <u>http://www.itu.int/itudoc/itu-t/rec/g/index.html</u>
- 3. What is the mass of a photon? http://www.desy.de/user/projects/Physics/photon_mass.html
- 4. The Photonics Dictionary http://www.laurin.com/DataCenter/Dictionary/CD/wrdlstm.htm
- 5. All-optical networks may one day form a national backbone http://www.laurin.com/DataCenter/Dictionary/CD/wrdlstm.htm
- 6. SPIE The International Society for Optical Engineering <u>http://www.spie.org/</u>
- 7. The Atom-Cavity Microscope Single Atoms Bound in Orbit by Single Photons <u>http://www.its.caltech.edu/~qoptics/atomorbits/</u>
- 8. Photonics-related Web Sites http://www.ee.virginia.edu/AEPL/labs/loqe/loqe_list.html
- 9. Semiconductor Optics Group AG Halbleiteroptik <u>http://www.physik.tu-darmstadt.de/hlo/</u>
- 10. Optics Express the international electronic journal of optics <u>http://www.opticsexpress.org/</u>
- 11. The Optical Interworking Forum http://www.oiforum.com/
- 12. American Institute of Physics http://www.aip.org/
- 13. Telecommunications Technology Resources Fiber Optic http://www.webexpert.net/vasilios/telecom/telecom.htm#FIBER
- 14. Massachusetts Institute of Technology (MIT) Lincoln Laboratory http://www.ll.mit.edu/index.html
- 15. All-Optical Networking Consortium TDM Slide Presentation http://www.ll.mit.edu/aon/TDMSlidePres.html
- 16. Photonics Online http://www2.photonicsonline.com/content/homepage/

- 17. Laser Focus World http://lfw.pennnet.com/home.cfm
- 18. LYNX Photonic Networks http://www.lynxpn.com/index.asp
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- 24. Photonic Switching Platform, Agilent Technologies. http://www.agilent.com/cm/photonicswitch/
- 25. "All-Optical Doesn't Mean Pure Optical," Ken Kelley, Teledotcom Article. http://www.teledotcom.com/article/TEL20010118S0005
- 26. "All-Optical Wavelength Switching Router," Internet Com Article. <u>http://www.clec-planet.com/tech/000512sorronto.htm</u>
- 27. "Atom lasers," Physics World Article. August 1999. http://physicsweb.org/article/world/12/8/8
- 28. "A Well Collimated Quasi-Continuous Atom Laser," http://physics.nist.gov/Divisions/Div842/Gp4/AtomOptics/intro.html
- 29. International Emergency Preference Scheme (IEPS) http://iepscheme.net.

Appendix G: Photonic Switching Physics

INTRODUCTION

It is difficult to adequately consider the future of photonic switching without touching on the tremendous advances occurring in solid physics, chemical and electrical engineering, and indeed even bioengineering. It was over 75 years ago that classical physics began to give way to new theories that were based on quantum mechanics. Today, photonic switching and numerous other related disciplines such as computer science are truly beginning to experience real world benefits from those early pioneers. One consequence of standing at a crossroads of substantial change is the inherent hazards associated with While on one hand the photonic switching systems being technology forecasting. marketed today could be characterized as early prototypes that are mostly based on extensions of existing technologies, a view too narrow in perspective would miss the very important advances that have already happened with respect to the utilization of phenomenon such as quantum tunneling and quantum well lasers. Indeed, it appears to be most appropriate to begin at this point to accept that fundamental changes in the rate of miniaturization improvements appear to be inevitable. With the principles of quantum mechanics making an ever increasing contribution to the science of communications and computing, and even the incorporation of biological research underway, it is becoming more difficult to bound the number of information links. Indeed, perhaps the most difficult challenge in exploring the NS/EP implications of photonic switching may lie in choosing if a particular area would best be presented in terms of scalar wave functions, magnetic vector fields, or indeed if both may be required. Considering that today there is still no unified physics theory upon which we may call upon to simplify our topic we are left to approach photonic switching by acknowledging that it is necessary to accept the fact that present day answers include the complex characteristics revealed by wave particle duality and electromagnetism in periodic dielectric materials.

One of the simplest views quantum mechanics provides is that it is the study of matter and radiation at an atomic level. Indeed, a good general characterization is that electromagnetic radiation is energy that is propagated through free space or through a material medium in the form of electromagnetic waves, such as radio waves, visible light, and gamma rays. The term also refers to the emission and transmission of such radiant energy. However, unlike classical physics where it is possible to render exact predictions, quantum mechanics is a world in which we can only calculate a probability for what will happen next. Correspondingly, we are presently left to accept as fact the notion that particles can move from point A to point B without going through the space in between.

Quantum mechanics was developed in the early 20th century because some experiments produced results that could not be explained by classical physics (the physics of Galileo Galilei, Sir Isaac Newton, James Clerk Maxwell, et al). Prior to quantum mechanics, for example, it was widely believed that electrons orbited the nucleus of an atom in a manner that resembled the planets orbiting the sun. Various experiments began to reveal that

classical physics contained dramatic flaws for examining very small (atomic size, where quantum mechanics is used) or very fast (near the speed of light, where relativity takes over) phenomenon. The standard model of particle physics provides a marvelously accurate description of the fundamental constituents and their interactions down to distances in the order of 10^{-16} cm. The most compelling and fundamental questions concerning physics, however, are found at the Planck scale of 10^{-33} cm, where space-time undergoes strong quantum fluctuations.

The most elementary, and familiar, quantity of information is the binary digit (bit), which can take on one of two values "0" or "1". Therefore, any physical realization of a bit needs a system with two well-defined states. A light switch, for example, where off represents "0" and on represents "1". A bit can also be represented, for example, by a certain voltage level in a logical circuit, a pulse of light, a pit in a compact disc, or the magnetization on a magnetic tape. In classical systems it is desirable to have the two states separated by a sufficiently large energy barrier so that the value of the bit cannot easily change in a spontaneous manner.

Two-state systems can also used to encode information in quantum systems and it is traditional to reference the two quantum states as 0> and 1>. The unique feature of quantum information technology is that a quantum system can be in a superposition of different states. The quantum bit can be in both the 0> state and the 1> state at the same time. This new dimension has no parallel in classical information theory and has led to the use of the word "qubit" being coined to distinguish the unique characteristic of a quantum bit. Additional information on qubits is contained in subsequent sections of this annex.

In the most simplistic terms quantum mechanics provides us with a way to describe the laws of the universe by treating everything as if it were a wave. Quantum mechanics provides the means to perform calculations such that we can view a cat, a book, or even a table as if each were a wave, much like visible waves on the water or even invisible radio waves. Continuing with this example we can imagine that if a rock is tossed into a pool and observed it is difficult to say where the wave that it creates starts or stops because it there are no distinct sharp edges. As the wave propagates it becomes increasingly difficult to say where the wave ends and the undisturbed part of the pool begins. If two rocks are thrown parallel into a pool, the waves created by both rocks will begin to overlap creating a number of patterns. Some points in the patterns will be motionless as the waves pass through them. At those points whenever the peak of one wave passes over it, the valley of the other wave passes at the same time. The two waves cancel each other leaving an undisturbed spot. At other points wave crests from both waves arrive at the same time. At these spots the fluctuation is greater than if only a single rock had been dropped into the pool. Quantum mechanics tells us that all matter, including a house, a bird, and a cat all exhibit wavelike properties.

The fundamental importance of quantum mechanics is described by the following phenomenon, which classical physics does not accurately resolve:

- a) Discreteness of energy;
- b) The wave-particle duality of light and matter;
- c) Quantum tunneling;
- d) The Heisenberg uncertainty principle;
- e) Spin of a particle.

Since each of these can contribute to a more clear understanding of the physics associated with photonic switching a brief, simplified, overview of each is provided.

Discreetness Of Energy

If we observe the spectrum of light emitted by energetic atoms (such as the orangeyellow light from sodium vapor street lights, or the blue-white light from mercury vapor lamps) it is easy to see that it is composed of individual lines of different colors. These lines represent the discrete energy levels of the electrons in those excited atoms. When an electron in a high-energy state jumps down to a lower one, the atom emits a photon of light, which corresponds to the exact energy difference of those two levels (conservation of energy). The greater the energy difference, the more energetic the photon will be, and the closer its color will be toward the violet end of the spectrum. If electrons were not restricted to discrete energy levels, the spectrum from an excited atom would be a continuous spread of colors from red to violet with no individual lines.

The concept of discrete energy levels is easily understood by considering the operation of a 3-way light bulb. A 50/100/150 watt bulb can only shine light at those three settings, and when you switch from one setting to the next, the power immediately jumps to the new setting instead of just gradually increasing.

It is the fact that electrons can only exist at discrete energy levels that prevents them from spiraling into the nucleus, as classical physics otherwise predicts. And it is this quantization of energy, along with other atomic properties that are quantized that gives quantum mechanics its name.

Wave-particle Duality of Light and Matter

In 1690 the Dutch mathematician-physicist Christiaan Huygens provided a mechanical explanation for reflection and refraction in his "Treatise on Light." In this work he formulated a theory on the nature of light in which he related light to wave motion. Then, in 1704 Sir Isaac Newton published "Opticks," which also included a comprehensive study of refraction, dispersion, diffraction, polarization, and a theoretical description of the corpuscular nature of light. Experiments supported each of these two theories. In 1923 Louis de Broglie hypothesized that a material particle could also exhibit wavelike properties, and in 1927 it was shown by Davisson and Germer that electrons can indeed behave like waves.

How can something be both a wave and a particle at the same time? A long held view of light was that it is a stream of particles that move up and down in a wavelike manner. This view was demonstrated to be incorrect. Light and matter exist as particles; what behaves like a wave is the probability of where a particle will be. The reason why light sometimes appears to act as a wave is because we are observing the accumulation of many light particles distributed over the probabilities of where each individual particle might be.

An imaginary dart tossing machine provides an insightful illustration. First we program the dart-tossing machine to have a 5% probability of hitting the bullseye, a 95% chance of hitting any other ring area on the dart board, and a zero probability of hitting any other place. Next imagine that the machine throws 100 darts. Since we can see each individual dart we know they behave like particles. However, we can also see an overall pattern on the board of a large ring of darts surrounding a small cluster in the center. The observable pattern is the accumulation of the individual darts over the probabilities of where each dart could have landed and represents the wavelike behavior of the darts.

Quantum Tunneling

Quantum tunneling is one of the most important practical phenomena to arise from quantum mechanics. As discussed previously, a wave demonstrates the range of probabilities where a particle can be. When a given probability wave encounters an energy barrier most of the wave will be reflected back, but a small portion of it will leak into the barrier. If the barrier is small enough, the wave that leaks through will continue on the other side of it. Even though the particle doesn't have enough energy to get over the barrier, there is still a small probability that it can tunnel right through it.

We can illustrate this by imagining that we are throwing a baseball against a wall. We know that we don't have enough energy to throw the baseball through the wall, so we always expect it to bounce back. Quantum mechanics, however, says that there is a small probability that the baseball could pass right through the wall, without causing any damage, and continue its flight on the other side. Of course with an object as large as a baseball the quantum tunneling probability is so small that we could probably throw the ball for billions of years and never actually observe a single instance of it going through the wall. However, quantum mechanics tells us that when we work with objects the size of an electron, that tunneling is an everyday fact of life.

Quantum mechanics also reveals the existence of an inverse quantum tunneling effect. When a particle encounters a drop in energy there is a small probability that it will be reflected back. In this case if we were rolling our baseball off a level flat level table there is a small chance that when the baseball reached the edge it would bounce back instead of falling to the floor. Again, for objects as large as a baseball the probably of observing such an event is unlikely but for massless particles of light like the photon this phenomenon it is a very real occurrence. Quantum tunneling enables us to construct transistors, computer chips, and other miniaturized circuits.



(Figure Courtesy of Sandia National Laboratories)

Figure 4 depicts a quantum-tunneling transistor with an on-off switch that exploits an electron's ability to pass through normally impenetrable energy barriers. The contacts and gates may be used to adjust the voltage between the upper quantum well, labeled "top QW," and the lower quantum well, "bottom QW." For this example, we consider that both upper and lower QW's are made of gallium arsenide and have a thickness in the range of 150 Ångströms. If the voltage is adequately adjusted it is possible for the electrons in the top QW to "tunnel through" the ordinarily insurmountable barrier of aluminum gallium arsenide, depicted as a saw-toothed energy barrier in the leftmost diagram, to the bottom QW. Tunneling occurs when the top QW and bottom QW accept electrons with the same energy and momentum states.

The Heisenberg Uncertainty Principle

People are most familiar with measuring things in the macroscopic world around them. Someone pulls out a tape measure and determines the length of a table. A state trooper aims his radar gun at a car and knows what direction the car is traveling, as well as how fast. People routinely obtain the information they seek and don't worry whether the measurement itself has changed what they were measuring. After all, what would be the point in measuring that a table is 80 cm long if the very act of measuring it changed its length?

At the atomic scale of quantum mechanics, however, measurement becomes a very delicate process. Consider, for example, that we wish to find out where an electron is and where it is going. One solution is to use an electron microscope. However, the very act of looking is based on the use of photons, and these photons may have enough momentum to change the course of the electron. This is like tossing a baseball into the air and trying to measure where it is and where it is going by bouncing another baseball off of it. The very act of measurement will have altered the course of the first ball tossed into the air. The second ball can be used to calculate where the tossed ball was but now we have no idea where it was going because we have altered the course by the measurement process.

Werner Heisenberg was the first to realize that certain pairs of measurements have an intrinsic uncertainty associated with them. For instance, if you have a very good idea of where something is located, then, to a certain extent, you must have a poor idea of how fast it is moving or in what direction. This is not evident in everyday life because any inherent uncertainty is well within the acceptable accuracy range we desire. If, however, we needed to measure the position of an object to an accuracy of a billionth of a billionth of a centimeter we would be trying to measure the positions of individual atoms and unless the temperature of the object could be cooled to absolute zero the atoms would be moving enough to make an accurate measurement very difficult to achieve.

Heisenberg's uncertainty principle stands in stark contrast to the laws of classical physics because one of the very foundations of science is the inherent capability to make accurate measurements. Quantum mechanics, however, reveals that it is virtually impossible to make exact measurements. Thus, the Heisenberg uncertainty principle is an accepted fact of nature.

Quantum electrodynamics, the part of quantum theory dealing with electromagnetic phenomena) predicts that empty space isn't really empty, so that there is no such thing as a perfect vacuum. Even in a vacuum, and even at a temperature of absolute zero, all kinds of particles pop in and out of existence as a consequence of the uncertainty principle. These particles pop into existence (in particle-antiparticle pairs), are present for a period of time, and then disappear. How long they can exist depends on how heavy the particles are -- the heavier the particles, the faster they must disappear, but even light particles can exist for very short periods of time. These particles are called virtual particles, because they normally can't be directly detected. The only time that it is possible to notice virtual particles is by observing their interactions with normal particles during the short time that they are present. One consequence of the existence of virtual particles is that there is an energy density associated with a vacuum.

The Spin Of A Particle

In the early twentieth century Otto Stern and Walther Gerlach performed an experiment whose results could not be explained by classical physics. Their experiment indicated that atomic particles have an intrinsic angular momentum, or spin, and that this spin is quantized; thus it can have only discrete values. Spin is a completely quantum mechanical property of a particle that cannot be explained by classical physics.

It is important to realize that the spin of an atomic particle is not actually a measure of how it is spinning. It is presently impossible to tell whether something as small as an electron is spinning at all. The word spin is merely a simple way of expressing the intrinsic angular momentum of a particle.

Modern day medical equipment such as magnetic resonance imaging is based on the fact that under certain conditions the spin of hydrogen nuclei can be flipped from one state to another. By measuring the location of these flips, a picture can be formed of where the hydrogen atoms, part of water, are in a body. Science takes advantage of the fact that tumors have a different water concentration from the surrounding tissue and thus they can be imaged.

The Schrödinger Equation

When considering objects as small as electrons, the equivalent to Newton's Laws is a quantum mechanics equation, which was originally discovered by Erwin Schrödinger. In quantum mechanics every particle is characterized by a wave function. Erwin Schrödinger's differential equation describes the nature of those wave functions. By using Schrödinger's equation it is possible to find the wave function that solves a particular problem in quantum mechanics. Often, it is impossible to find an exact solution to the equation, so certain assumptions are used in order to obtain an approximate answer for a particular problem. Schrödinger's equation was immediately recognized for the practical benefits it brought to the use of quantum mechanics. This equation cannot be derived from any fundamental law but is based on several well established principles of physics.

The basic ingredients in Schrödinger's Equation are:

- a. The equation, which relates the wavelength of an object to its momentum;
- b. Conservation of energy;
- c. Knowledge about how waves, such as how water waves behave;
- d. Accounting for forces, which act on the object by using changes in potential energy.

$$i\hbar \frac{\partial}{\partial t} \psi(r,t) = -\frac{\hbar^2}{2m} \nabla^2 \psi(r,t) + V(r,t) \psi(r,t)$$

i is the imaginary number, $\sqrt{-1}$

 \hbar is Plank's constant divided by 2π : 1.05459 X 10⁻³⁴ jcule=second $\psi(r,l)$ is the wave function, defined over space and time *m* is the mass of the particle

 ∇^2 is the Laplacian operator:

 $V(\mathbf{r},t)$ is the potential energy influencing the particle

Figure 5 - Schrödinger's Equation

Once the equation is set up for a particular situation a computer is usually engaged to try to solve it. If a suitably close solution is found Schrödinger's equation results are expressed as a wave function.

A Wave Packet

As stated in previously the Schrödinger equation for a particular problem cannot always be solved exactly. However, when there is no force acting upon a particle its potential energy is zero and the Schrödinger equation for the particle can be exactly solved. The solution to a free particle is known as a wave packet, which initially looks just like a Gaussian bell curve. Wave packets can provide a useful way to find approximate solutions to problems which otherwise could not be easily solved.

First, a wave packet is assumed to initially describe the particle under study. Then, when the particle encounters a force such that its potential energy is no longer zero, that force modifies the wave packet. The goal is to find accurate and fast ways to propagate the wave packet so that it still represents the particle at a later point in time.

Boise-Einstein Condensate (BEC)

A BEC is a macroscopic quantum phenomenon that S. Bose and Albert Einstein first predicted in the 1924. Quantum theory was still developing and was being applied to microscopic systems, such as individual particles and atoms. Einstein applied the quantum theory with the new concept of Bose statistics to an ideal gas of identical atoms that were at thermal equilibrium and trapped in a box. His prediction was that at sufficiently low temperatures (i.e., close to absolute zero) the particles would accumulate in the lowest quantum state in the box, giving rise to a new state of matter with numerous unusual properties. This prediction was validated in Boulder Colorado 71 years later in 1995.

A BEC is incredibly fragile and it is believed to be the most fragile material that has ever existed. Physicists are currently making very small quantities of BEC; only a few million atoms at a time. There are many similarities between a BEC and laser light. What makes laser light different from ordinary light is that all the photons are exactly the same. They are the same color and they are all going in the same direction. It is this uniqueness that allows laser light to be applied to achieve incredible results in telecommunications and other applications; simply because we can control laser light so much better than we could control ordinary light from light bulbs. A BEC shares this same uniqueness with laser light. All the atoms in the condensate are exactly the same. So this means that it is now possible to exert much better control over atoms: where they are and how fast they are moving. In fact, due to a BEC we now can control atoms to the extent that the uncertainty principle will allow. From the similarities with laser light, it is a reasonable to expect that BEC is a good candidate for creating very sensitive measurement instruments and for constructing very tiny structures, such as those used in telecommunications and in computer chips.



Figure 6 – Image Courtesy of Mike Matthews

JILA research team working in cooperation with NIST

Figure 6 displays a color enhanced image (i.e., false) to illustrate the velocity distribution of a cloud of rubidium atoms at three points (depicted in order from left to right)

- (a) just before the appearance of the Bose-Einstein condensate;
- (b) just after the appearance of the condensate;
- (c) after further evaporation left a sample of nearly pure condensate.

In Figure 6 the field of view of each frame is 200 x 270 micrometers, and corresponds to the distance the atoms have moved in about 1/20 of a second. The color corresponds to the number of atoms at each velocity, with red being the fewest and white being the most. Areas appearing white and light blue indicate lower velocities. Velocity-distribution data confirms the discovery of a new state of matter, the Bose-Einstein condensate. The two right-most images, corresponding to lower temperatures, show multiple atoms coalescing into a single macroscopic quantum state.

In the early part of the 20th century, as quantum mechanics was being developed, it was found that all particles can be divided into two classes. The first category of particles is known as Fermions. Ferimons were named after Enrico Fermi and they obey the "Pauli exclusion principle;" namely that no two identical Fermions can be in the same quantum state at the same time. This means that Fermionic systems will have many energetic

particles flying around even as the temperature goes down to absolute zero, since only one particle can be in the lowest energy state.

The second category of particles is called Bosons, named after Satyendra Nath Bose. Bose, a physicist from India, worked out the statistics for photons. Albert Einstein adapted the work by Bose and applied it to other Bosonic particles and atoms. Einstein found that not only is it possible for two Bosons to share a quantum state, but that they actually prefer being in the same state. He predicted that at a finite temperature, almost all of the particles in a Bosonic system would congregate in the ground state. When this happens, the quantum wave functions of each particle start to overlap; the atoms get locked into phase with each other, and loose their individual identity. This phenomena was named "Bose-Einstein condensation." Using this effect it is possible to put a large group of atoms in a single quantum state in a manner very similar to laser verses normal light waves.

Four Wave Multiplexing

Four-wave mixing is an example of a nonlinear optical phenomenon. Whereas linear optics includes most if not all optics that we encounter in our daily lives, so-called because of the linear behavior of the electric field component of light as it propagates. The wave nature of light comes from the field components of light - the electric and magnetic fields that oscillate as light travels.

In nonlinear optics, the linear behavior no longer works because of special interaction between light and the media it is in. The behavior of light is never exactly linear because there are always nonlinear components in every medium including a vacuum. Normally these components are so small they can be ignored, but in certain media like crystals, and in Bose-Einstein condensates, these components are large enough that nonlinear effects can be put to work.

What are these effects and why would someone go to the trouble of creating them? The effects can either be a change in polarization or a change in wavelength. Polarization effects can be used in optical switches in lasers and wavelength effects can take a laser at one wavelength and half it, such as when an infrared laser is changed to blue.

In four wave multiplexing three waves, of frequency $\omega 1$, $\omega 2$ and $\omega 3$, are sent into a nonlinear crystal. The exchange of energy and momentum between the waves, mediated by the nonlinear crystal, results in the production of a fourth wave with frequency $\omega 4 = \omega 1 + \omega 2 - \omega 3$. A quantum mechanical description of this process is that two photons from separate beams annihilate in the crystal and produce two new photons. The energy and momentum of one of these photons adds to the third beam, while the other photon corresponds to a new, fourth beam. There is an analogous process with matter waves. The four-wave mixing process arises from collisions between pairs of atoms from two matter-wave beams $\omega 1$ and $\omega 2$. One pair of atoms scatters in the direction of the third, incident matter-wave beam_ and amplifies it. By the conservation of energy and momentum, the other pair of atoms produces a fourth, separate beam $\omega 4$. A false-color

image of the experimental atomic distribution showing the fourth small wave packet generated by the matter-wave mixing process. A Bose-Einstein condensate was divided into three momentum states using a sequence of pulsed laser beams. The nonlinear interaction between the atoms produces a fourth momentum state. The distribution of atoms in the four momentum states is easily observed after they have had sufficient time to separate.

Quantum Mechanics

Today's photonic switches employ a wide range of technological solutions that includes: space switching, MEMS, and thermal inkjets. These solutions are based on familiar, and proven fundamentals in which a longstanding operational basis has been incorporated into the design. Photonic switching will likely continue to be deployed along these conservative lines as long as requirements can be satisfied and costs controlled. In looking out toward the not so distant future, however, it is clear that quantum mechanics is poised to play an ever-increasing role with respect not only with regard to switching systems but also to the entire communications infrastructure. As advances with photonic crystals begins to be deployed in applications such as reflecting dielectric or waveguides the promise of "quantum" leaps into new directions that could vastly change the communications industry in an unprecedented manner.

Scientists, such as, Albert Einstein and Erwin Schrödinger have made the early 20th century remembered as a time of great discoveries. In some cases it has required more than 75 years to perform laboratory experiments that can successfully demonstrate the correctness of this early work. However, it is clear today that quantum-well lasers, photonic crystals, bandgap engineering, and other developments based on QM advancements will inevitably be called on at an ever increasing rate to satisfy requirements. The capabilities of QM bring help that can be used to solve future NS/EP requirements and points to the benefits of associating the evolving photonic switching arena of telecommunications with QM principles.

Bell's Inequality Principle and Local Theories of Quantum Mechanics

Entanglement has long been the source of numerous puzzling experiments that directly associate the predictions of QM theories with telecommunications. Perhaps the oldest and best know physics example of enganglement involving telecommunications is an age-old paradox that can assist us to present insightful, and more practical, illustrations in subsequent sections in this annex. Consider, for example, that a source emits photons that are entangled in a $|\Psi^+\rangle$ state, and one photon is switched to Alice and the other photon is switched to Bob. It is certain that whatever basis Alice chooses to measure the polarization of her photon, she will obtain "0" or "1" with equal probability; the actual results being completely random. And, as long as Bob chooses the same linear basis, he will always obtain the same result. Entanglement properties provide the means for Alice to predict with certainty what Bob's result will be, even if they are widely separated and not in contact with each other.

The entanglement property of quantum mechanics has been an area of physics experimentation for decades; going back to Einstein, Podolsky and Rosen (EPR). The phenomenon has two key elements: locality and reality. Locality means that no physical action can instantly go from Alice's apparatus to Bob's while reality, in this example, requires that there must be some element in the physical world that allows Alice to know Bob's results.

Following this line of reasoning, and assuming the validity of both locality and reality, John S. Bell investigated possible correlations in which Alice and Bob choose bases that are at oblique angles. For three arbitrary angles, α , β and γ , the following inequality must be satisfied

$$N(1_{\alpha}, 1_{\beta}) \leq N(1_{\alpha}, 1_{\gamma}) + N(1_{\beta}, 0_{\gamma})$$

where $N(1_{\alpha}, 1_{\beta})$ is the number of times Alice obtains "1" with her apparatus at orientation a and Bob obtains "1" with orientation β , and so on. Quantum mechanics predicts that $N(1_{\alpha}, 1_{\beta}) = \frac{1}{2}N_0 \cos^2(\alpha \beta)$ and $N(1_{\beta}, 0_{\gamma}) = \frac{1}{2}N_0 \sin^2(\beta - \gamma)$, the of pairs emitted where N_0 is number by the source. The inequality is violated if we choose the angles such that $(\alpha - \beta) = (\beta - \gamma) = 30$. This has been confirmed experimentally many times and implies that one of the assumptions of Bell's inequality (e.g. locality or reality) must be in conflict with quantum mechanics. The experiments have generally believed to be evidence for non-locality, though this is by no means the only possible explanation. To show that Bell's inequality is violated in a two-particle experiment, it is necessary to perform a statistical experiment: the violation cannot be demonstrated with a single measurement. However, the situation is very different with three-particle entangled states such as the Greenberger-Horne-Zeilinger (GHZ) states further described below. Contradictions between the EPR assumptions and QM arise for individual events. Readers that have a further interest in work pertaining to the violation of Bell's inequality should consult the recommended reading annex of this paper.

Any quantum mechanical system can be used as a qubit providing that it is possible to define one of its states as 0 and another as 1). From a practical point of view it is useful to have states that are obviously distinguishable. Furthermore, it is desirable to have reasonably long state lifetimes so that the quantum information is not lost to the environment through decoherence. Photons, electrons, atoms, quantum dots and so on can all be used as qubits. It is also possible to use both internal states, such as the energy levels in an atom, and external states, such as the direction of propagation of a particle, as qubits.

In quantum communications theory the fact that quantum uncertainty comes into play does not actually imply a loss of information. In fact, superposition is actually an asset, as can be seen if we consider systems comprised of more than one qubit. What happens when we try to encode two bits of information onto two quantum particles? The straightforward approach would be to code one bit of information onto each qubit separately. This leads to four possibilities: $0\rangle_1 0\rangle_2 0\rangle_1 1\rangle_2 1\rangle_1 0\rangle_2$ and $1\rangle_1 1\rangle_2$ where $0\rangle_1 1\rangle_2$ describes the situation where the first qubit has the value "0" and the second qubit has the value "1", and so forth. This approach corresponds exactly to a classical coding four possibilities would represent "00", "01", "10" and "11".

Just like classical encoding, four different possibilities can be represented by the four Bell states, so the total amount of information that can be encoded onto the two qubits is still constrained to the combinations offered by two bits. Now, however, it is possible to encode the information in such a way that neither of the two qubits carries any well defined information on their own; all of the information is encoded in their joint properties.

To encode more data onto quantum systems, it is only necessary to use more qubits. More qubits result in higher dimensions of entanglement. For example the so-called Greenberger-Horne-Zeilinger (GHZ) states, are entangled superpositions of three qubits. In the state $\frac{1}{2} (000 + 111)$ all three qubits are either "0" or "1" but none of the qubits has a well defined value on its own. Measurement of any one qubit will immediately result in the other two qubits attaining the same value.

Qubit Notation

Any two-state system can be used as a qubit. Many examples that have been successfully demonstrated including the polarization of photons, the directions of electron or nuclear spins, energy levels in atoms or quantum dots and the propagation directions of particles. It is customary to distinguish the system by means of the following notation:

$ 0\rangle$ $ 1\rangle$	Qubit
$\left \mathrm{V} ight angle\left \mathrm{H} ight angle$	Photon, linear polarization
$\left L \right\rangle \left R \right\rangle$	Photon, circular polarization
$\ket{+}\ket{-}$	Electron, nucleus spin
$\left \mathrm{g} \right\rangle \left \mathrm{e} \right\rangle$	Atoms, quantum dots, energy levels
$\left a\right\rangle\left b\right\rangle$	Any quantum system, spatial modes

Even though it has been show that GHZ states lead to significant contradictions between a local realistic view and quantum mechanics, it has been discovered that such states are significant in many quantum-information and quantum-computation schemes. For example, if we consider 000 and 111 to be the binary representations of "0" and "7", respectively, the GHZ state simply represents the coherent superposition $(1/\sqrt{2})("0"\rangle + "7"\rangle)$. If a linear quantum computer has such a state as its input, it will process the superposition such that its output will be the superposition of the results for each input. This is what leads to the potentially massive parallelism of quantum computers.

It is apparent that the basis chosen for encoding the quantum information, and the states chosen to represent 0 and 1, are both arbitrary. For example, if polarization measured in a given direction has been chosen as the basis, we could further agree to the horizontal polarization of а photon with "0" and identify its vertical polarization with "1." However, we could choose to rotate the plane in which we measure the polarization by 45°. The states in this new "conjugate" basis, 0' and 1', are related to the previous states by a 45° Hilbert space rotation

$$0' \rangle = (1/\sqrt{2})(0) + 1\rangle)$$
$$1' \rangle = (1/\sqrt{2})(0) 7\rangle)$$

This rotation is known as a Hadamard transformation. When spin is used to encode information we can change the basis by a simple polarization rotation; when the directions of propagation are used, a beam splitter will suffice. It is important to note that conjugate bases cannot be used at the same time, although the possibility of switching between various bases - most notably between conjugate bases - is the foundation of the single-photon method of quantum cryptography.

Quantum Dense Coding

Entangled states render a more advanced scheme for encoding information. From the four Bell states it is clearly possible to switch from any one of the four states to any other one by performing an operation on only one of the two qubits. For example, to switch from Ψ^+ to Ψ simply applying a phase shift to the second qubit when it is "0" (i.e. $0 \rangle \rightarrow 0 \rangle$, $1 \rangle \rightarrow 1 \rangle$). The state ϕ^+ is obtained by flipping the second qubit, while the state ϕ can be obtained by the combination of a phase shift and flipping.

All three of the operations are unitary and they do not change the total probability of finding the system in the states $0\rangle$ and $1\rangle$. Four unitary operations are usually associated with Bell states: (1) the phase shift (2) the bit flip, (3) the combined phase-shift/bit-flip, and (4) the identity operator. The identity operator does not change the state on which it operates.

Quantum entanglement says that Bob can send two bits of information to Alice using just one photon, as long as Alice has access to both qubits and is able to determine which of the four Bell states they are in. This scheme has been put into practice using polarization-entangled photons. It relies on the process of spontaneous parametric downconversion in a crystal to produce entangled states of very high quality and intensity. The nonlinear properties of the crystal convert a single ultraviolet photon into a pair of infrared photons with entangled polarization.

The interaction Hamiltonian of the process of spontaneous parametric down-conversion can be written:

$$\hat{H}_{\text{int}}(t) = \int_{-L}^{0} dz \chi^{(2)} E_p^{(+)}(z,t) \hat{E}_1^{(-)}(z,t) \hat{E}_2^{(-)}(z,t) + \text{H.c.},$$

where $x^{(2)}$ is the second-order susceptibility, $E_p^{(+)}$ denotes the positive-frequency part of the electric-field amplitude of the pump field, and $E_1^{(-)}$ ($E_2^{(-)}$) is the negative-frequency part of the electric-field operator of down-converted field 1. The nonlinear crystal extends from z=-L to z=0. The symbol H.c. denotes the Hermitian conjugate.

Quantum-Well Lasers

The driving force for the rapid development of two dimensional semiconductor structures, so called quantum wells, is their potential for various electronics applications. Such devices based on quantum wells are widely used already today, but are predicted to considerably gain in importance in the future, in particular within the areas of optoelectronics and high-speed devices. We encounter examples on such applications in daily life, e.g. laser and detector structures in CD players or cash registers, high-frequency modulators in cellular phones and other telecommunication applications. This rapid development has been possible by the introduction of sophisticated growth techniques to manufacture high quality semiconductor structures. These advanced techniques allow growth of a semiconductor structure with a precision down to a single atomic layer. This means in turn that quantum wells, treated as a pure hypothetic exercise in basic quantum mechanics courses just 20 years ago, can now be realized in these semiconductor quantum structures with an Ångström precision.

If a given semiconductor material with a small energy gap is sandwiched between energy barriers from a semiconductor material with a larger energy gap, a quantum well is formed between the barriers. Typical layer thicknesses are just a limited number of atomic layers, say 10-100 Ångström. Once an electron is captured into this well, the probability to escape from the well is limited. Moreover, the restriction on the movement of the electron into this plane, a "two-dimensional world", affects also the energy of the electron as compared to a "free" electron in the three-dimensional case. These so-called quantization effects will result in allowed energy bands, whose energy positions are dependent on the height and width of the barrier and can be calculated by means of fundamental quantum mechanics.

Quantum Well Laser Structures

As an indirect band semiconductor, Silicon has been responsible for great progress in electronic circuit miniaturization. Over the past few years a direct band semiconductor,

Galium Arsenide, has been facilitating a change in the scale of what we expect from miniaturization. Due to the ever evolving epitaxial techniques, such as molecular beam epitaxy and metal organic chemical vapor deposition, it is now becoming possible to grow semiconductor layers on the order of tens of Ångströms. Since these distances are so small, a layer thickness can be compared to that of the deBroglie wavelength. Therefore, we must begin to view the optoelectronic effects of such devices quantum mechanically.



Figure 7 – Sample Semiconductor Materials and the Color Spectrum

One of the difficulties with growing alternating structures is the lattice mismatch factor which accounts for the built in strain effects within the quantum structures. As will be seen, this effect can be utilized to our advantage. When two semiconductors with different bandgaps are grown on top of one another a discontinuity at the band edge is produced. For example, in a GaAs and AlxGa1-xAs system there is a 65% direct bandgap difference in the conduction band, and 35% valence band discontinuity. One excellent example of unique qualities of this system is the realization of a very good match of lattice constants between GaAs and AlGaAs. By growing alternate layers of GaAs and AlxGa1-xAs it is possible to form a structure wherein quantum wells are formed in the conduction as well as the valence band. Within this structure electrons and holes are
firmly confined in the growth direction, but are free to move perpendicular to the growth direction.

If we consider a quantum well structure comprised of AlAs/GaAs/AlAs then within the plane of the quantum well, single particle wavefunctions are plane waves, but the motion in the crystal growth direction yields wavefunctions which are sinusoidal within the barrier and exponentially decaying outside of the barrier. This factor makes it clear that proper quantum confinement between alternating structures is achieved only if the barrier is thick enough so that the wavefunctions of neighboring wells do not overlap. Such coupling between wells occurs at a barrier thickness that is <50Å, and for a thickness >50Å the wells are uncoupled and the electronic properties in a single and multi-quantum well are similar.

In an ordinary semiconductor device the physics of allowed momentum states of the electrons and holes are treated as continuous variables since the dimensions are much larger than the deBriglie wavelength, λ_D . However, on the other end of the dimensional spectrum, mainly where the physical size approaches λ_D , density of states changes to account for the quantization of the momentum in the direction of the growth. For a finite confining width, the quasi two dimensional density of states in the energy interval dE for a quantum well is given by

$$N_{2D}(E) dE = \frac{m^{\bullet}}{\pi^2 \hbar^2 L_z} dE$$
[1]

]

where m* is the effective mass of the conduction band electron. Lz is the width of the confining region. The quasi-two dimensional density of states formed in a quantum well in the z-direction is independent of energy and has a staircase characteristic. Equation 1 also describes the light and heavy hole density of states with m* taking on the value of the light and heavy hole effective mass. The density of states in the x-y plane is three dimensional and has the usual form, illustrated in equation 2,

$$N_{3D}(E) dE = \frac{\sqrt{2} m_0^2 E^{\frac{3}{2}} dE}{\pi^2 \hbar^3}$$
[2]

where m_o is the mass of the electron, E the energy of the state, π and h carry their traditional meanings. The total energy of the electron can be calculated by solving the Schrödinger equation, illustrated in equation 3:

$$\left\{-\frac{\hbar^2}{2\,m^*}\,\nabla^2 + V(z)\right\}\Psi(x,y,z) = E\,\Psi(x,y,z)$$
[3]

with the total energy being represented by equation 4

$$E(l,k_x,k_y) = \frac{\hbar^2}{2m^*} \left(\frac{\pi^2 l^2}{L_x^2} + k_x^2 + k_y^2 \right)$$
(4)

where L_Z is the width of the barrier, $l=\{1,2,3,4...\}$ and it identifies the band index. Equation 4 is also valid for the valence band light and heavy holes by replacing m* by a suitable effective mass. Equation 4 reveals that as the dimensions of Lz decrease, the quantized bound state energies change to higher energy values. Hence, if the well is on the order of tens of Ångströms wide and the barrier is not tall enough, states above the lowermost state may not be altogether bound. In fact, the wavefunction of the state above the ground state may coalesce with the continuum states. This consequence is directly related to a problem that deals with a delta function potential with a negative strength, (i.e. V(x)= -A d(x)). For this potential one bound state exists. This means that no matter how small the well width, one bound state will always be present. In addition, it is important to note that electrons in a specific sub-band, (i.e. l=1), will recombine with heavy or light holes of the same sub-band.

Analogous to a standard laser system, for example the two level model which incorporates an electromagnetic field and an atom within the field changing between one energy state and another, the semiconductor laser theory is quite similar. Both of the processes involve an action known as the population inversion. In the classic case, one can consider a two level system where through pumping energy excitation of atoms from the ground state (l=0 state) into an excited state, the l=2 state, occurs. Atoms then make a rapid transition from l=2 to l=1, and level 1 has a long lifetime. Therefore, the complete picture shows that the atoms are piling up at level 1, assuming a rapid pumping is occurring, and a population inversion has built up between levels l=1 and l=0. Now the transition between level 1 and the ground state occurs, and this particular progression is often referred to as a laser transition. The change in number of photons, nph with respect to time will be directly proportional to the difference between the number of atoms in the l=1 (N1) and the ground state (N₀), as depicted in equation 5,

$$\frac{dn_{ph}}{dt} \propto (N_1 - N_0)$$
[5]

if the number of photons increase with time and there is amplification, demonstrating the primary action of the laser.

In a semiconductor system one deals primarily with electrons and holes. The primary concern is the stimulated recombination of holes and electrons in direct semiconductor materials. Moreover, speaking of direct band materials is suited to emphasize that appropriate physical interpretation of optical transitions do take place within the indirect materials, but the strength of the radiation is much weaker than that of direct. Thus, it is more relevant to focus on direct optical transitions.

The actual recombination process involved is illustrated in 6 below

electron + hole $\longrightarrow h \upsilon$ [6]

where an electron and a hole recombine and emit a photon of a frequency v.

One of the most important aspects of quantum well lasers is that some of the lowest threshold currents have been measured within them. Currents on the order of tens of milliamps, and emission wavelengths between 695nm and 820nm have been measured in AlGaAs/GaAs quantum wells. Usually, single quantum well lasers pose a problem of poor optical confinement. This is one of the primary reasons that why today we utilize multiple, instead of single, quantum well structures

There is, however, the question of how many wells do we use? The answer to the question is a function of many variables. For instance, the built in strain could cause problems related to defects. Therefore, one has to properly define the well and barrier width, the materials to use, and factor in the strain between the materials. It is a well known fact, that strains in multiwell quantum structures can play a positive role. For example, in GaAs strain removes the degeneracy between the heavy and light hole bands at k=0. Tensile strain displaces the light hole band above the heavy hole band, and compressive strain places the light hole below the heavy hole band. Tensile and compressive strains have been found to reduce threshold currents.

Appendix H: Suggested Readings

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