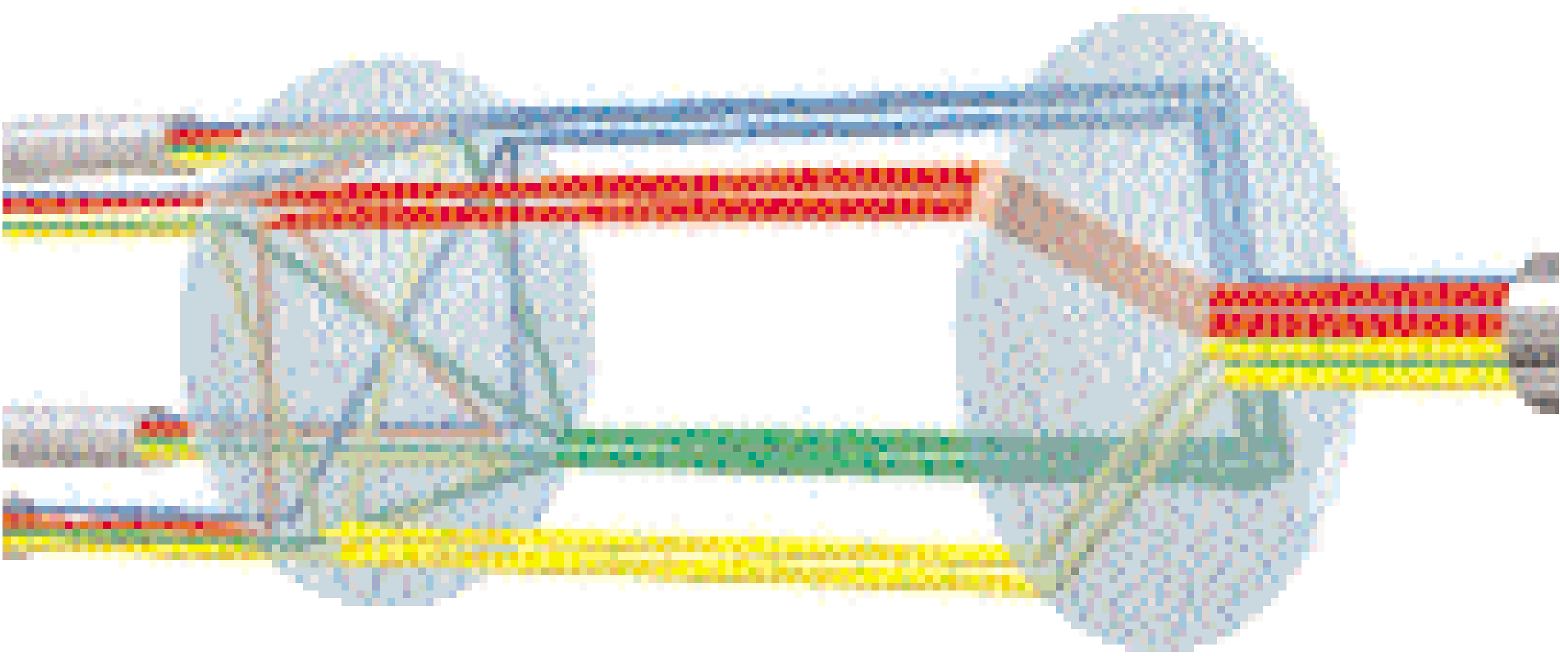


OPTICAL ROUTER sends packets of data streaming along different colored wavelengths, frome one fiber to another.

Today's network architects have already begun to build the Optical Internet using technologies that can switch some or all of the light signals in one incoming optical fiber to one or several outgoing fibers. The new-generation Optical Internet will serve as a high-speed mail delivery vehicle that will bring units of data called packets to a point nearby a recipient. There the time-consuming process of sorting out which packet goes where—the Internet equivalent of the local post office—will fall to electronic routers from companies such as Cisco Systems and Juniper Networks. Over time, even this task of switching individual packets may be taken over by routers that use photons, not electrons, for processing.

The IP packet is the Internet's basic unit of currency. In today's networks, every e-mail message gets chopped into thousands of packets, which are routed over different pathways and reassembled at a final destination using the Internet Protocol (IP). The routers, together with other networking equipment, convert data from lightwaves to electronic signals in order to read the packets and send them along to their final destination: a mail server, where they are reassembled into a coherent message before a synthesized voice proclaims, "You've got mail!" The key is that the routers all along the way can easily read the address of each IP packet.

The all-optical network that does the heavy hauling may serve as only one stage in the evolution toward a truly all-optical network, however. When networks routinely shuttle terabits (trillions of bits) a second, the conversion step into electronics may prove too costly both in time and money. In coming years, a router may have to break down a data stream carrying 40 gigabits (billions of bits) a second over a single wavelength into 16 parallel electronic data streams, each transmitting 2.5 gigabits a second within the router. Moving a massive number of packets every second through multiple layers of electronics in a router can lead to congestion and degrade network performance.

Light to Light

Because of this, network engineers are contemplating a solution that will use lightwaves to process lightwaves and optical switches that can redirect packets at blindingly fast speeds. The technology for photonic routing switches is still in its infancy. Creation of a photonic packet-switched network will depend on overcoming multiple technological hurdles equivalent to those that had to be addressed by electronics engineers from the mid-1950s to the mid-1970s, going from individual capacitors and resistors soldered onto a circuit board to monolithic integrated circuits.

Nevertheless, the quest has begun. The Defense Advanced Research Projects Agency (DARPA) has funded programs in optical packet switching at the University of California at Santa Barbara, Telcordia Technologies in Morristown, N.J., Princeton University and Stanford University. Alcatel in France, the Technical University of Denmark and

The ultimate all-optical network will require dramatic advances in technologies that use one lightwave to imprint information on another

ROUTING PACKETS WITH LIGHT

by Daniel J. Blumenthal

the University of Strathclyde in Scotland have also launched research efforts.

A potential communications standard for photonic packet switching in future networks is known as All-Optical Label Swapping (AOLS). In AOLS, individual IP packets or groups of packets get tagged with an optical label. The IP packet is like an envelope with an address on the front (called the header) and contents inside (called the payload). AOLS attaches a label to the packet by placing it, say, in front of the header. The use of labels resembles packing into the same mailbag all letters going through the same set of major cities on the way to their final destination. Postal workers read only the label at each intermediate routing point, not each individual envelope.

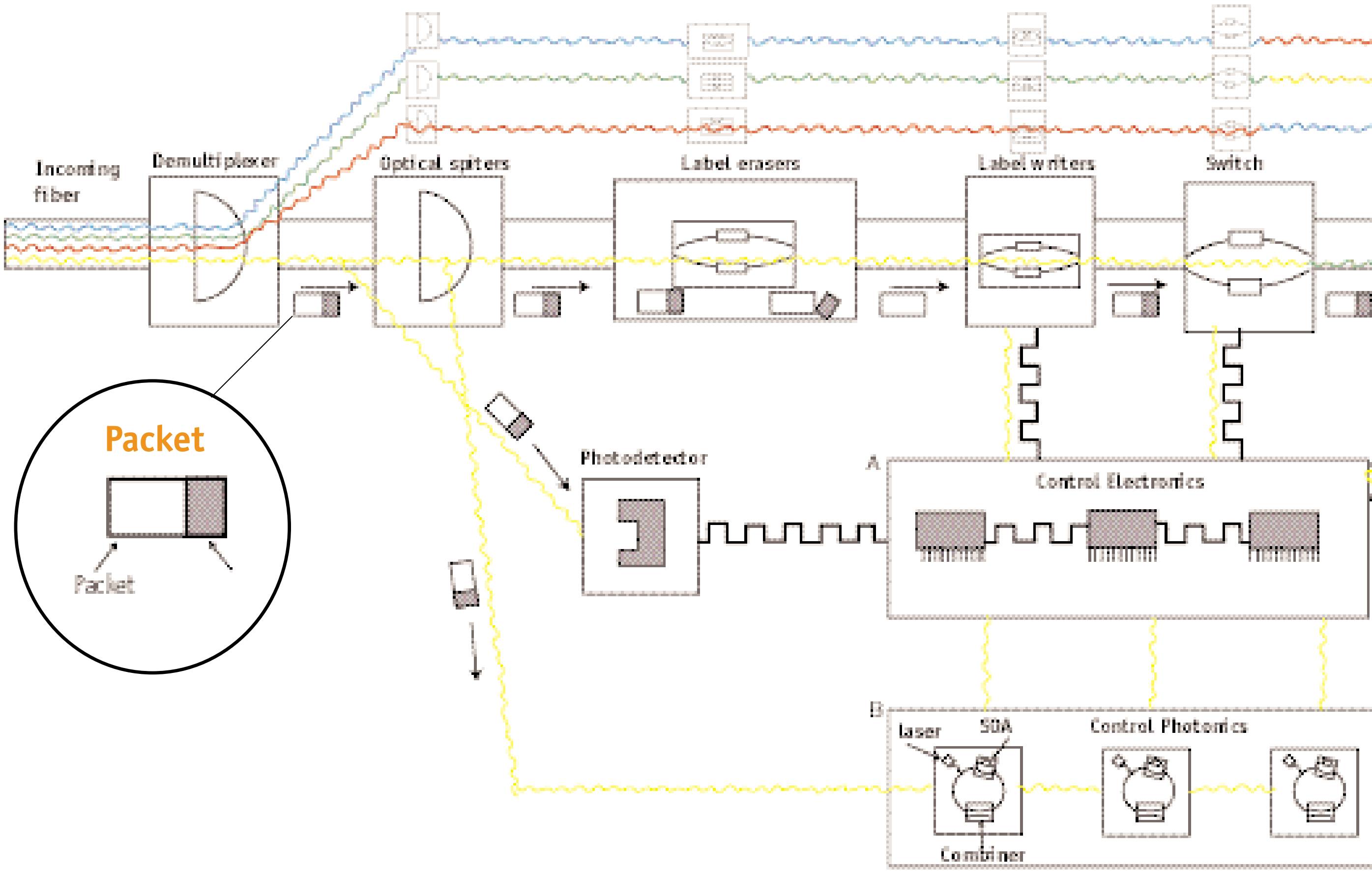
In a communications network, an optical router will look only at the smaller label and determine which output fiber or wavelength to send the packet to, instead of reading the header inside the packet. Current photonic technologies do not make this task easy. Optical components that perform the function of the integrated circuit elements that read and process a label exist mostly as laboratory demonstrations that have not made their way into the commercial mainstream.

Take something as simple as the buffers used for temporary storage of the bits in a packet. In designing an electronic router, an engineer would hold the packet in a buffer that is similar to the dynamic random-access memory (DRAM) used in computers. Photons cannot be stored easily, however. So designers must then figure out ways to buffer the packet by complex optical circuits that do not hold the photons still but rather corral the pulses of light into a holding area similar to an automobile traffic circle. Other approaches use techniques that match how long it takes the pulses in a packet to move through a switch. They do so by sending the pulses through a predetermined length of fiber. The time it takes to traverse this "detour" fiber equals the time needed by the switch to strip off the packet label and read the routing information it contains.

Optical buffers on laboratory benchtops are currently hundreds of times larger than the submicron-size dimensions of their electronic buffer counterparts. It is not known if the optical version of the dense conglomeration of transistors found in the Pentium chip will ever come to be a reality.

Besides buffers, logic circuits that can process labels based on light controlling light have also been shown in the lab but are a long way from being engineered into a full-scale router. The first examples of photonic routers will therefore still rely partly on electronics. A packet that enters a first-generation AOLS router will have a small amount of its optical energy diverted down a separate pathway, where it gets converted by a photodetector into an electronic copy of the packet and label. The label goes to circuitry that reads its contents and computes the next pathway for the packet along the network. The electronic processor generates a new label, attaches it to the original packet, and sends a control signal to the switch to specify a particular fiber or wavelength along which

Optical Packet-Switching Network



ALL-OPTICAL LABEL SWAPPING is an emerging standard for photonic switching of individual packets. A packet enters the switch, gets stripped off and read electronically (a) or with lightwave processing elements (b). The processors decide on which wavelength and fiber a packet should exit the switch. A new label gets placed on the packet, which then gets switched to an output fiber.

the packet should travel. Despite the need to make an optoelectronic conversion for the tiny label, perhaps 20 bits in size, the optical switches can forgo electronic processing of the much larger packet, which may range from 40 to literally thousands of bytes. The big packet moves through the switch at the higher-speed optical bit rate. Making the conversion for the entire packet might be prohibitive in cost as well as consuming power and space for electronic equipment.

Once the label has been processed, the packet finally arrives at the physical elements that switch it from the input to the output fiber. Optical switching elements pose another major engineering challenge, because the switching components must be able to send a packet to a new fiber or wavelength in a nanosecond or less. Several technologies have emerged that are capable of switching packets at the desired speeds. One example is the semiconductor-optical amplifier, a device that uses stimulated emission of light, the same process that drives a laser, as the basis for switching.

To switch a signal on an incoming fiber to any of many outgoing ones, the amplifier forms an optical bridge between the desired input and output fibers. When a data-carrying optical signal reaches the bridge, an electric current in a control signal injects electrons and "holes" (areas where electrons are absent) into the amplifier. Light entering the amplifier causes the electrons and holes to combine with one another, giving off more photons that are exact copies of the optical signal trying to cross the bridge. Once the signal reaches a certain level of power, it moves from one side of the bridge to the other. When the control current is shut off, light at the amplifier input is absorbed and does not make it through to the output fiber. Although the control signal that opens the gateway is electronic, the stream of photons carrying packets races through the switch without getting converted to an electronic signal.

The technology remains in early development. Investigators have devised fast switches with up to eight incoming and outgoing fibers each, although for marketable products they will need to create switches with hundreds or thousands of input and output ports.

Semiconductor-optical amplifiers may also perform a vital role in realizing a technology that can transfer a stream of bits directly from one lightwave to another. This wavelength converter can switch packets to multiple output fibers by combining the technology with a device called a wavelength multiplexer that, much like a prism, can separate light into its individual colors. The

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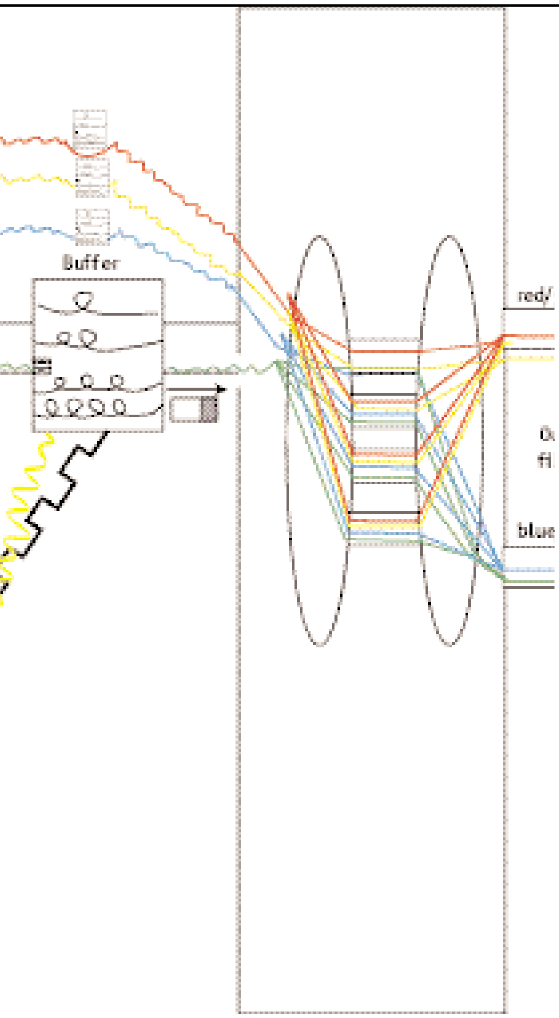

Optical Packet Caption Title TK

1. Data on an incoming fiber gets separated by wavelength into different pathways in the switch

2. An optical splitter makes a copy of the packet and sends it either to a control module, which may be either electronic (A) or photonic (B).The control module reads only the label, discarding the rest of the packet.

3. The other copy of the packet goes to a label eraser, where the label is removed.

4. A label writer then writes a new label upon receipt of a signal from the control modules—denoting the next destination where the packet is to be sent.

5. Another signal from a control module directs the switch to send a packet from one wavelength to another. (The same process occurs for packets being channeled on the incoming blue, green and red wavelengths.)

6. An optical buffer holds a packet until the control module directs it to send the packet through a multiplexer.

7. A multiplexer directs the packet to one of the output fibers.

wavelength converter will determine how to route packets to avoid switching conflicts. If two packets in different fibers both need to be transferred to the red wavelength in a given output fiber, the wavelength converter will route one of the packets to a green wavelength to ensure that they don't conflict.

Experimental converters have employed photonic integrated-circuit (PIC) technology, the optical equivalent of integrating electronic components on microchips. In a converter built with PICs, light from a laser moves along waveguides, similar to optical fibers. In some types of optical processing, a wavelength carrying a stream of bits interacts with another wavelength, imprinting information on it. The light-to-light transfer occurs when the stream of optical bits causes the waveguide to change the phase of the recipient lightwave, which then exits into an output fiber. A change in phase might represent a digital one and no change a zero.

To make converters feasible, researchers have devoted massive efforts to the development of tunable lasers that can be set to different wavelengths onto which bits from incoming packets can be modulated. Currently laboratory lasers allow an incoming data stream to be switched to any of 80 wavelengths, and that number will grow to hundreds in the future.

To 160 Gigabits and Beyond

Ultimately even the decisions on how to route a packet may by necessity become all-optical. As packet speeds on a given wavelength exceed 160 gigabits a second, a typical packet will race through the switch in a nanosecond, whereas it would take 100 nanoseconds to process a label using electronics. In essence, the address label will have become larger than the envelope (packet) onto which it is affixed. Increasing the speed at which the label moves through the processor—to beyond 100 gigabits a second—might tax the electronic control circuitry (although new exotic electronic technologies that operate past 100 gigahertz are being tested).

In anticipation of this problem, a few laboratories have fashioned early prototypes of ultrahigh-speed optical logic gates that can be built from the same technology used to build light-controlled switches. These devices—developed at Princeton , the M.I.T. Lincoln Laboratory and British Telecom Labs, among others—utilize different configurations of semiconductor-optical amplifiers or other optical materials to implement simple optical Boolean logic gates (that is, AND, XOR and NOT) that can process light signals moving at speeds in excess of 250 gigabits a second.

These gates have made extremely simple packet-routing decisions in the laboratory but cannot yet be scaled up to the number needed to make complex routing decisions. Still, device integration and new optical-switch technologies may one day make all-optical control possible, marking the advent of the all-optical packet switch. If such issues can be resolved, a packet might travel from New York City to Los Angeles through IP routers and never pass through electronics. SA

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Further Information

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