Progress in Optical Networking

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ABSTRACT

This article summarizes the present state of optical networking, how we got to this point, and what needs to be done to complete the job. The point of departure is an assumed future two-level structure in which the transport is by means of steadily growing interconnected all-optical islands of transparency, while the remainder of the communication layers are based on IP, both levels being managed by an MPLS-based control plane. After reviewing why such networks are becoming inevitable, a review is given of the various optical layer technology and architecture bottlenecks that have had to be solved. Issues that remain center on increasing the number of channels and reducing the technology costs.

PERSPECTIVE

Optical networks are those in which the dominant physical layer technology for transport is optical fiber. They can be opaque or all-optical, and can be single-wavelength or based on dense wavelength division multiplexing (DWDM).

In opaque networks the path between end users is interrupted at intermediate nodes by optical-electronic-optical (OEO) conversion operations. When this introduces dependencies on bit rate and even bit pattern syntax, any hope of transparency to these attributes is lost. The traditional synchronous optical network/synchronous digital hierarchy (SONET/SDH) is an opaque single-wavelength system. Today's widely installed WDM systems are opaque too, the intermediate nodes being either electronic add-drop multiplexers or digital crossconnects, or perhaps misnamed "optical add-drop multiplexers" (OADMs) or "optical crossconnects" (OXCs) that actually have electronic bit handling in the signal path. None of these opaque systems have the versatility and power of the all-optical network. In this article, the terms OADM and OXC will refer to the purely optical add-drop multiplexer and crossconnect, respectively.

In all-optical networks, each connection (lightpath) is totally optical, or at least totally transparent, except at the end nodes. Today, all-optical networks are emerging as a multibillion dollar industry, apparently the dominant transport architecture of the future, because of increased need for their functionality and because a number of technology advances have made these advantages accessible.

The principal driver is the seemingly inexhaustible human appetite for more bandwidth per user and more users, and this bandwidth-greedy world seems to be converging to a two-layer communication infrastructure (Fig. 1): packet-by-packet IP routers supported by an optical transport layer providing quasistatic paths. The ATM function of traffic engineering (e.g., quality of service, QoS, guarantees) is being absorbed into IP, and the transport capabilities of SONET/SDH (e.g., protection and accommodation of various bit rates through tributaries) is being absorbed by the optical layer. Therefore, what has been four layers converges to two. For nomadic situations, the physical layer would be wireless, but this part of the physical layer will not be discussed here.

The dominant role assumed by the all-optical approach applies not only in *long-haul* telco networks, where the lightpaths can be hundreds to thousands of kilometers in length, but also the *metro* environment (tens to several hundreds of kilometers in length) and to some extent the *access* (1–10 or so km). There is some question whether *LANs* (0–1 km) will ever go all-optical. The long-haul and metro structures are usually thought of as the domain of the interexchange carriers, incumbent local exchange carriers, or competitive local exchange carriers; in other words, facilities service providers. Instances of the access infrastructure are typically owned by the established carriers, large corporations, or IP service providers.

Recent technology developments that are now making the all-optical solution quite workable include particularly the invention of practical all-optical crossconnects (OXCs) and all-optical add-drop multiplexers (OADMs) that enable the evolution from simply point-to-point WDM links to full networks. An OXC is simply a large photonic switch having N full-duplex ports, each of which can connect to any other, and also itself. For WDM service, the OADM is a 2 x 2 degenerate form of the $N \times N$ OXC that extracts and reinserts certain lightpaths for local use and expresses the others through. At each wavelength, the OADM has two full-duplex ports on the facilities side and two on the local

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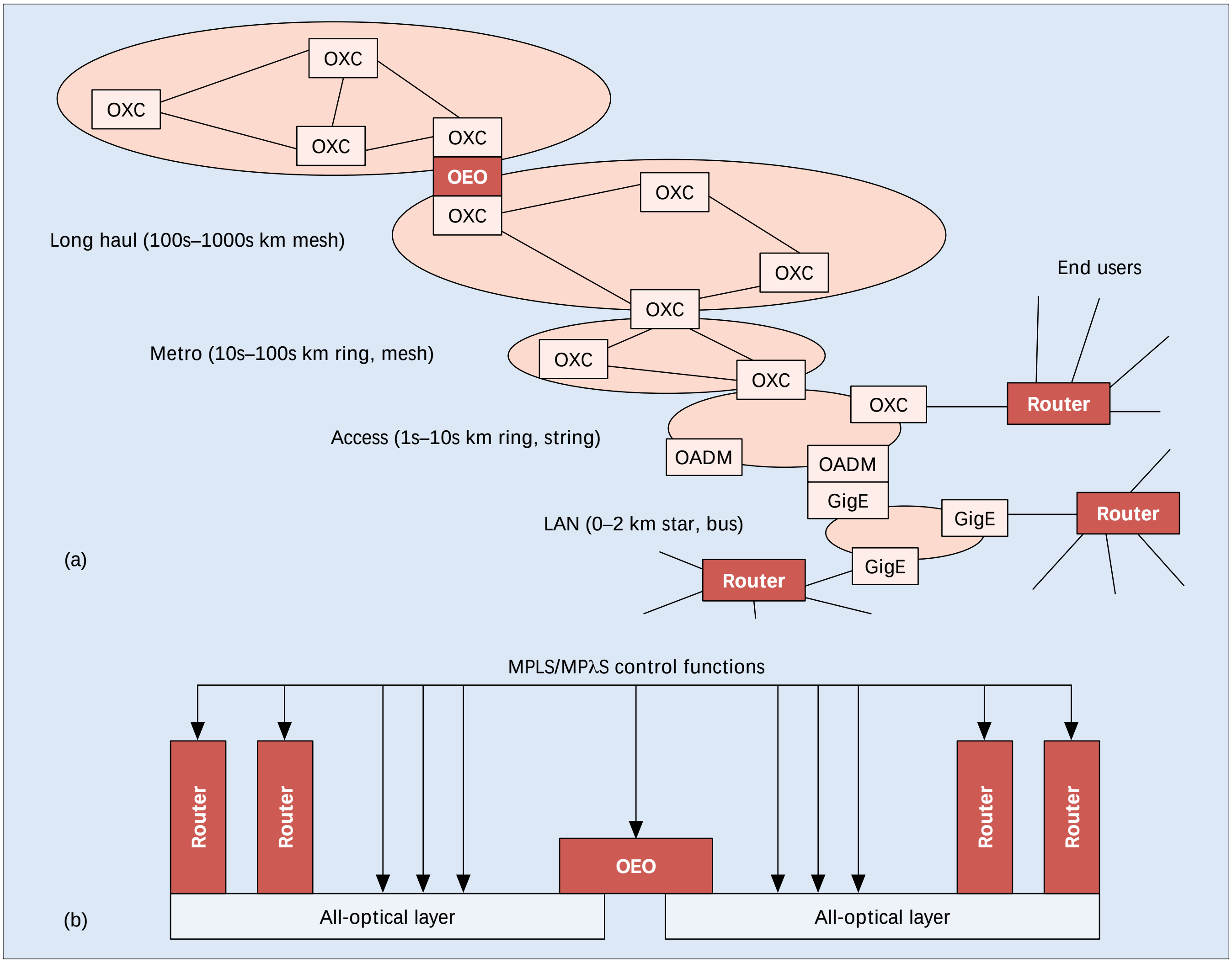

Figure 1. *The optical and IP layers: a) the topology view: islands of all-optical transparency connect to each other via OEO and to users via IP routers; b) the equivalent layer view.*

side. Usually, for the passthrough state at a given wavelength, the two line-side ports are connected to each other, and for the add-drop state each line-side full-duplex port terminates locally. In general, with the OXC, any one of N full-duplex ports can connect to any other one or to itself, and any of the ports can play the role of a line side or local side port.

This brief article first reviews why all-optical networks are important, assesses where the evolution stands today (late 2000), and then gives an account of some of the principal obstacles that still remain to the complete fulfillment of the possibilities, which are not only exciting but crucial if the pace of the information revolution is to be sustained.

Why All-Optical Networks?

The most obvious reason for one to want an all-optical network is, of course, the stupendous bandwidth available in optical fiber, but there are other significant motivations that are not so obvious. As every reader will know by now, the bandwidth in just the 1.5 μ band of each of the world's single-mode fibers is some 25,000 GHz, about 1000 times the entire usable radio frequency (RF) spectrum on the planet Earth (with its oxygen absorption at higher frequencies). Mining the fiber bandwidth by deploying more and more highly resolved WDM channels propagating over ever-increasing distances has been a slow, steady process of developing better, more stable photonic components, and also introducing new fibers and amplifiers that have more bandwidth real estate than their predecessors. At this writing, commercial systems with up to 160 OC-48 (10 Gb/s) channels have been announced that can communicate over paths thousands of kilometers long, uninterrupted by OEO conversions.

Perhaps the second most important parameter of an all-optical WDM lightpath is the complete lack of protocol dependency of such a path. Except for matters of link budget, it doesn't even matter what the bit rate is. This valuable digital *transparency* has the important practical consequences that old protocols may be given artificial respiration to extend their lifetimes, and new ones may be brought online just as quickly as though one were dealing with simply some piece of bare fiber between the endpoints.

As the world rapidly converges to the two-layer model, IP becomes suitably updated, particularly to add QoS to a basically "shoot-and-hope" architecture, and the old fixed transport physical layer of copper, microwave, or whatever, becomes optical, or actually all-optical.

A third advantage, not often appreciated, is functional simplicity, which has important consequences in lowering first cost and offering service lifetime savings by making problem determination and maintenance potentially much simpler than they are with the traditional fiber-plus-OEO systems. The full realization of the benefits of this functional simplicity is requiring a certain fortitude on the part of the providers who have long been used to looking at the bits at every one of many OEO points along the path. It takes some getting used to to realize that not only can't you look at the bits in an all-optical network, you don't really have to, for reasons that will be discussed.

When one resists the temptation to look at the bits at intermediate nodes in the network, all the advantages of "cut-through" come into the picture. Each signal path no longer needs to climb its way through several layers of software or firmware and back down again at each intermediate node, accumulating in the process software path length delays and exposure to the many possible failure modes intrinsic in very high-speed electronics and all software. The large first cost and service lifetime cost of communication software and its supporting hardware are present only in the end nodes in an all-optical network.

Finally, there is the intrinsic robustness of an all-optical network. As will be discussed, the new physical layer, which replaces the old one based on copper or fiber-plus-OEO, can provide not only basic transport, but also several other networkwide rerouting functions that allow the optical layer to exhibit extremely high service availability, and to do so without the bit handling required in SONET/SDH protection switching or IP packet rerouting.

What Is the Current Status?

As the world rapidly converges to the two-layer model, IP becomes suitably updated, particularly to add QoS to a basically "shoot-and-hope" architecture, and the old fixed transport physical layer of copper, microwave, or whatever becomes optical, or actually all-optical. The way in which the all-optical character is being introduced is that large and growing *islands of transparency* are being formed out of WDM links, stitched together by OXCs and OADMs as they become available, the OEO boundaries between islands being defined jurisdictionally or by propagation budget considerations (typically attenuation or dispersion of one sort or another).

So, as Fig. 1a shows, the picture rapidly emerging at the end of 2000 can be viewed topologically as all-optical islands with IP routers attached to serve end users and with OEOs (typically digital crossconnects) to stitch those islands together that are in different jurisdictions. Or if you like to think in layers (Fig. 1b), there is an underlying all-optical layer upon which either IP routers lead to higher user-oriented protocol layers or OEO intermediaries lead to the next island. It will take time, but in the long run, SONET/SDH is likely to survive only in the archeological sense that 125 μs framing remains the basis of the TDM structure supporting the IP packets.

As usual, neither the layer view nor the network map view capture the whole story, because control and management have been left out. For this purpose, as shown by the arrows at the top of Fig. 1b, the optical routing nodes (OXCs and OADMs) communicate with each other and to the bit-aware world of routers and the OEO intermediary through some non-traffic-bearing wavelength, which could presumably be the optical supervisory channel within each all-optical island.

How Did We Get Here?

The first rumblings leading to all-optical networks occurred in Bellcore and British Telecom about 15 years ago, the first laboratory prototype (Lambdanet of Bellcore) appeared in 1990, and the first deployed network (Rainbow-1 of IBM) in 1991. The first commercial DWDM products (Next Generation Lightwave Network of AT&T and 9729 Muxmaster of IBM) hit the streets in 1995. Lambdanet and Rainbow were star topology networks using the broadcast-and-select principle, which is very wasteful of wavelengths and optical power. The other early systems were even simpler, just point-to-point WDM links.

By 1996, WDM fiber pipes were being extensively installed, followed within two years by a few primitive OADMs with frozen paths. Today, dynamically switchable OADMs are commercially available, and large-N OXCs will shortly begin to ship, preceded by an interim phase where opaque OEO substitutes, with their lack of scalability and their nontransparency, are temporarily filling the gap.

At the technical level, these 10 years of progress are mainly due to advances in six areas:

- Improved architectural understanding
- Developments in purely optical crossconnects
- More channels of higher bit rate
- New kinds of fiber and amplifiers
- Longer lightpaths
- Lower technology costs

We now discuss each of these in order.

Network Architecture

Several years ago, optical networking architects were concerned with medium access control (MAC) protocols for optical packet switching, the combinatorics of wavelength conversion, and optimum forms of network topology. As the field has matured, it has become clear that the more important problems relate to the network "control plane" and to ensuring the service integrity of the optical layer, which increasingly carries large quasistatically routed chunks of precious traffic on which depends the viable operation of many institutions, public and private.

One of the exciting things about the two-layer story is that both the optical networking community and the IP router community have begun to agree that the way to control both layers is by multiprotocol label switching (MPLS), or, in the case of the optical layer, a slightly modified version, multiprotocol lambda switching (MPλS). Each of these control planes has two phases, the transient one in which paths are set up, and the steady state or traffic phase in which the state information that has been set up in each node to define the paths then acts to forward packets in a way that provides much of the long-missing QoS capability. The control phases of these two emerging standards provide a unified, agreed-upon way for the nodes in the IP and optical layers to set up and take down their portions of virtual point-to-point IP packet connections between end users. There are a number of reasons for MPxS to replace the many variants in current practice in the lower communication layers (especially SONET/SDH) and the IP layer. Not only are both these traditional control software families very much vendor-dependent within themselves, the SONET/SDH and IP control structures being totally unlike each other, but both are too slow to satisfy anticipated needs, not just for protection, but for restoration and also provisioning, all three of which will be discussed shortly.

The only serious MPLS vs. MPλS disagreement seems to be whether the control entity within each set of IP routers forming the IP layer will be topologically aware of just what pattern of OXC traversals constitutes the lightpath across an optical island, or whether the optical layer will set these up autonomously and tell the IP layer where the endpoints are without saying which sequence of OXCs constitutes the lightpath. At present writing, it would appear that the latter style of operation is likely to prevail, at least initially.

The first of the optical layer integrity processes to receive attention has been *protection switching*, the millisecond-scale substitution of a new lightpath for a failed one. This action usually requires precanned algorithms akin to the SONET/SDH protection switching algorithms, and invokes only a very localized part of the network, usually no more than a single span, string, or ring of nodes. Whereas conventional protection switching is often triggered by some bit-level process, in optical protection switching the trigger can be loss of optical signal-to-noise ratio (OSNR).

The second is *restoration*, the replacement of the failed optical path within the island by another, that is, providing a new backup for the former one, now playing the role of the service path. Since one can allow minutes or even longer to do this, it is possible not only to have real-time software do the job, but to involve much larger portions of the network in the process than can be tolerated for protection switching. Figure 2 illustrates the difference between span protection, ring protection, and mesh restoration for a representative all-optical island.

Finally, there is *provisioning* or *reconfiguration*, in which one relieves stranded bandwidth conditions, arranges for the brokering of bandwidth between service providers using the optical facility or even setting up rent-a-wavelength conditions. Provisioning/reconfiguration can involve optimization over the entire optical network island or even several of them, since minutes or hours are allowable for their completion.

All these actions are today expected to be available in the access, metro, and long-haul environments.

Purely Optical Crossconnects

The precipitous arrival, within the last year, of adequate technology for large all-optical crossconnects has been a transforming event. Suddenly, the all-optical, topologically complex, wavelength-routed network, which had seemed like a distant vision, is very close to product reality. While the need for such an OXC network element has been clear for years, for a while it seemed as though the all-optical parameter would have to be compromised by doing the internode route switching electronically, thus completely destroying the protocol independence and most other advantages of all-optical outlined earlier in this article. This OEO digression was short-lived, however. Those who persisted with the all-optical vision were rewarded by seeing micro-electromechanical systems (MEMS) progress from 2D optical switches to 3D. 2D is a direct analog of the crossbar and involves N^2 popup mirrors to deflect collimated light from some input port to an output port, as in Fig. 3a. On the other hand, 3D (Fig. 3b) embodies only $2N$ mirrors, N of them directing the inputs toward distinct outputs and another N directing the outputs to connect to the inputs. The advantage of 3D is therefore linear scalability with port count (compared to quadratic for 2D), but at the expense of analog mirror tilt control vs. binary for 2D.

Assuming economical, stable solutions to the analog control problem, 3D has other advantages. A 3D OXC of a given large port count (say thousands) can be used for managing whole fibers as well as wavelengths, can be partitioned in arbitrary ways to accommodate different wavelength counts or fiber counts, and avoids the very large cost and attenuation hit of the interconnections required to form large-N multistage (e.g., Clos) nonblocking $N \times N$ structures from small-N 2D subcomponents, which have so far achieved only 16 x 16 or at most 32 x 32 size.

However, if the OXC is to be used just for WDM switching, we encounter the problem that today there is no easy way to do protocol-transparent wavelength shifting all-optically. One might suppose that a path within the OXC between any input at wavelength 1 and any out-

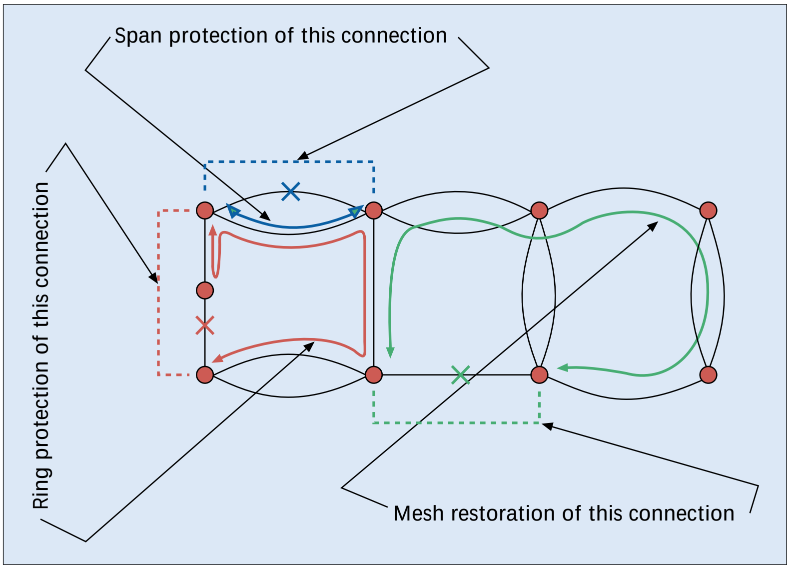

Figure 2. *Protection and restoration example: a) span protection, switch to a parallel line; b) ring protection ("BLSR-like" example shown); c) mesh restoration.*

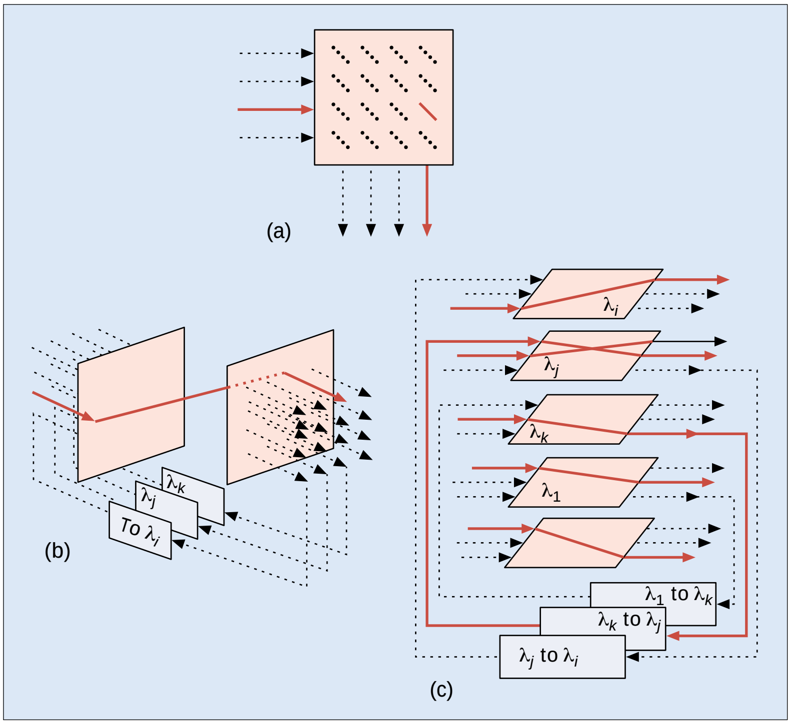

Figure 3. *Purely optical crossconnects (OXCs): a) 2D using binary (popup) mirrors; b) 3D using mirrors with analog control, showing an attached wavelength converter pool; c) multiplane architecture using multiple 2D modules, showing an attached converter pool.*

put that wants to see wavelength 2 would be essentially useless anyhow, so why build in these paths (i.e., why have a completely nonblocking structure)? This argument has led some to embrace the highly blocking "multiplane" architecture of Fig. 3c. Each plane, which can be a 2D chip, handles all the fibers and user ports for one wavelength. Some of the ports are allocated to connect to and from OEO wavelength converters. Each conversion uses up two ports, one "from" and the other "to," so that the total overhead, when conversion is required, is two in and two out (i.e., two full-duplex ports).

In the 3D architecture of Fig. 3b, wavelength conversion is handled the same way, albeit with greater flexibility: a pool of wavelength converters attaches to certain ports, and when conversion is required of one input, that one is connected to a converter input port, and the converter's output port connects to the proper output. In the 3D OXC of Fig. 3c, the availability of tunable lasers can reduce the size of the converter pool required, since any input port can reach any output port. In the multiplane arrangement, one converter is required for every combination of "from" and "to" wavelengths that is likely to occur, a much more expensive proposition requiring many fixed-tuned lasers.

More Channels of Higher Bit Rate

While intrinsically each single fiber should be able to support tens of thousands of multigigabit channels, subdividing the available bandwidth into ever increasing numbers of WDM pipes has proved to be a slow, incremental process. Whereas the standard International Telecommunication Union 100 GHz channel spacing was all anyone dared use not three years ago, today some systems use 50 GHz, while 25 GHz is being actively pursued. The main problems in crowding many channels into the fiber passband have been not just increasing modulation rates, but especially laser frequency instabilities, imperfect selectivity of optical receiver filters, limits on optical amplifier bandwidth, and propagation defects that arise when many channels of adequate power are driven through a single fiber.

Laser frequency drift is now commonly dealt with by use of "wavelength locker" components that slave the laser frequency to that of an inline Fabry-Perot cavity, in the same way broadcast radio transmitters have always been locked to quartz crystals that were part of the master oscillator's circuitry. What is lacking from the optical art is the equivalent of frequency synthesizers that provide a choice of digitally switchable output frequencies. For lack of optical frequency synthesis, what is emerging instead is tunable laser technology, where, for maximum accuracy, what is agile may be the Fabry-Perot reference which the laser then tracks.

Laser chirp (fast FM under modulation) is not so harmful in itself; it is the time smearing during transmission along the fiber because of chromatic dispersion that causes the problem, increasingly an issue as bit rates and distances go up. The "reach" of a laser product is rated mostly according to how much chirp it has along with how much power it can develop. Chirp is commonly reduced by externally on-off modulating a continuous wave (CW) laser output. Today, most lasers for service at gigabit rates come complete with electroabsorption modulators already integrated on the same chip. External modulator components, which are currently required for 10 Gb/s and up, are showing steady improvements in extinction ratio and chirp under modulation.

Optical receiver filters are steadily improving. For the last few years, filters made from multilayer manifolds of thin films have dominated the field, principally because they provide such good temperature stability and flexible tailoring of the flatness of the passband top (important so that the laser can be allowed to have nonzero drift) and the steepness of descent at the passband edges (to minimize adjacent channel crosstalk). In reaction to the success of thin film filters, steady improvements are being made in passband shape control with two older methods: planar arrayed waveguide gratings, which are capable of mass production since they are fabricated lithographically, and fiber Bragg gratings written into pieces of fiber, which take advantage of fiber component production techniques.

Wavelength interleavers help to relieve the problem of shaping the band edges. At the receiver input, the even and odd channels are directed to two separate outputs, and the final filters are attached to these. Now, since the originally adjacent channels are no longer present in what the final filter sees, the band edge dropoff of the final filters can be much more permissive than for the conventional case where the two adjacent channels are presented to a filter that must reject both of them on its own.

Meanwhile, what of the bit rate produced by digital electronics? Whatever happened to the "electronic bottleneck," the expected rock wall limit on bit rate in electronics? As so often happens, the rock wall has turned out to be more permeable than predicted. When one can afford the cost, 10 Gb drivers and receivers have become so common that this bit rate (OC-192) is rapidly replacing OC-48 (2.5 Gb/s) as the *lingua franca* of telco backbone communication. In the backbone, OC-768 (40 Gb/s) is being tested for service usage.

And yet, when it comes to LANs with their extreme cost pressures, 10 Gb Ethernet (10 GigE) is being introduced in the form of four-wavelength coarse WDM where each wavelength carries one fourth the bit rate. (In this way, the WDM camel seems to be getting its nose under the local area tent flap even before WDM significantly penetrates the access environment).

Are we approaching the end of the line for entirely electronic bit rates? Nobody knows.

New Kinds of Fiber and Amplifiers

As part of the drive for more channels, even the width of the familiar 1.5 μ low-attenuation band has been increased. In Lucent's new "AllWave" fiber the large high attenuation peak normally separating the 1.5 and 1.3 μ transmission bands has been almost completely eliminated by dramatic reduction of the OH ion content of the glass.. The same old sloping Rayleigh scattering attenuation curve that causes 1.3 to have higher attenuation than 1.5 is still there, but we can now think of the two bands as potentially just one.

Meanwhile, Corning has introduced Metrocore, a special fiber with a dispersion characteristic (delay vs. wavelength) that is the negative of the chirp introduced by directly modulated lasers. For the modest distance ranges and cost sensitivity of the metro application, this allows considerable savings on lasers and modulators.

Up to now, an even more constraining bandwidth limitation than the fiber passband has been the range of wavelengths over which significant optical amplification was available. The classical C-band (1530–1570 nm.) coverage of Erbium doped-fiber amplifiers (EDFAs) within which amplification is most efficient has been augmented by adding parallel gain capability of EDFAs in the S-band (1450–1530) and L-band (1570–1620) at the cost of higher pump powers at new pump wavelengths driving longer sections of doped fiber for those two bands.

In the search for more amplifier wavelength coverage, the old Raman amplifier idea has been dusted off and given a new life. Raman amplification has at least two desirable properties. First, amplification can be made to take place at any wavelength, as shown in Fig. 4a. The molecules in the glass are pumped into an excited state and then Raman amplification, a molecular process not associated with any particular spectral line, takes place within a band more than 90 nm wide on the long-wavelength (lower

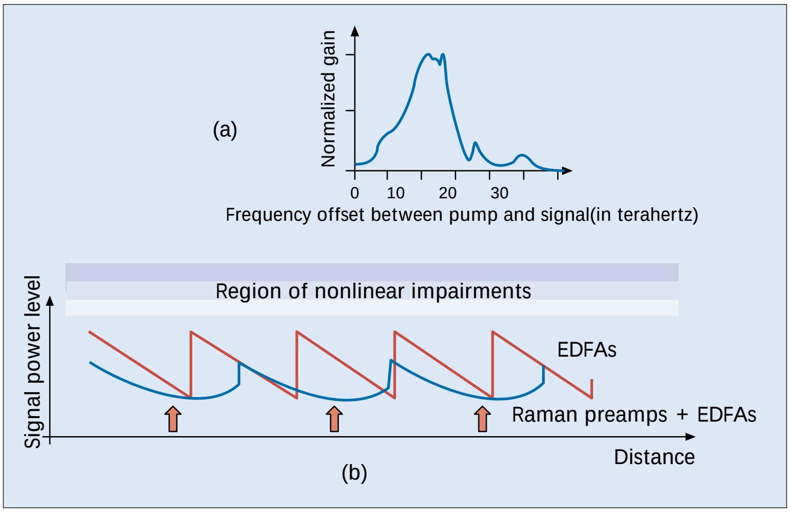

Figure 4. *Better amplifiers: a) Raman amplification spectrum; b) curves of optical power level vs. distance showing Erbium amplifiers alone (red) andRaman amplifiers as preamps for EDFAs (blue).*

energy) side of whatever the pump wavelength happens to be. Second, amplification can now take place along the propagating fiber itself, not just within a special section of specially doped fiber within the amplifier component, as with EDFAs. Third, some of the impairments due to high power levels in multiple wavelengths can be mitigated, such as four-wave mixing (third order harmonic distortion). This is done by directing the Raman pump energy backward up the fiber. Figure 4b compares the use of EDFAs alone (red curve) with the use of less powerful EDFAs preceded by Raman preamplification in the upstream fiber (blue curve). Raman amplification extends the distance covered by doing the amplification where the signal is already fairly weak, rather than counting on high amplifier output powers to carry the signal all the way to the receiver. The overall result is greater amplifier station spacing at a given or greater bit rate for existing installations, plus decreased impairments because maximum power level along the link can be lower.

One big problem in realizing the full potential of Raman amplifiers is the need to develop high pump powers at arbitrary wavelengths. Many exotic solutions are emerging. Another problem is crosstalk between on-off modulated channels at the points along the link where the Raman pump is being exhausted. These are marked with vertical arrows in Fig. 4b.

Thus, in summary, it appears that the way the world has only partially successfully kept up with the growth of bandwidth demand is to keep increasing the number of WDM channels, pushing electronic speeds, and manufacturing and installing more and better fibers and amplifiers. No one of these has proved sufficient by itself.

Longer All-Optical Lightpaths

In the last two years, it has proved possible to extend all-optical paths to great distances, with respect to both number of kilometers traversed and number of hops (i.e., number of WDM demux and remux stages traversed).

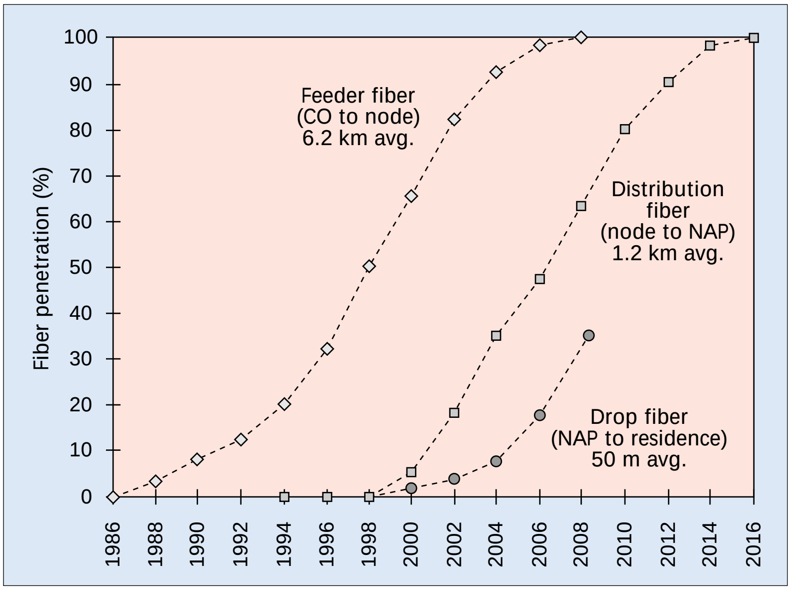

Figure 5. *The expected deployment of fiber to the premises will open up the backbone to precipitously increasing fiber exhaust (projections courtesy Corning, Inc.).*

Single wavelength paths of global (e.g., trans-Pacific) lengths have long been possible by placing optical amplifiers at such short spacings (e.g., 30 km.) that the OSNR is kept to high values everywhere along the path. The same philosophy has been applied to WDM lightpaths where distances of 4000 km at 160 OC-48 wavelengths have been achieved. Several new tricks come into play. Raman amplification with backward-directed pumping is used to avoid situations where the WDM signals achieve high power levels that are sustained over large distances. Chromatic dispersion effects are compensated by prechirping each transmitted signal.

Achieving large numbers of hops can sometimes be done by careful choices of which paths occupy which wavelengths; for example the longest path might use 1532 nm, the Erbium amplification peak. This ultimately becomes uninteresting because the arrival of new connection requests can then lead to the need to disrupt all user traffic by reassignment of different connections to different wavelengths. By carefully providing fixed equalization of the irregularities in the Erbium amplification spectrum (which also involves regulating amplifier input power levels), minimizing connector loss differentials, and other such measures, it is now possible to have a completely flat set of lightpaths such that a new connection request need not lead to interruption of the existing ones in order to make some optimum rearrangement.

Technology Costs

The level of competition in the optical component business has exploded in the last five years, and this, combined with economies of scale, manufacturing automation, and design for manufacturability, is leading to some modest cost reductions. One example will suffice. In 1995, individual distributed feedback laser diodes sold for $4000 each in small quantities, whereas today exactly equivalent such devices are $1000. This improvement curve is not nearly as impressive as the equivalent for LSI electronics, but the improvement is helpful.

What Remains to Be Done?

The fundamentally most urgent need is to increase the number of WDM channels, their length, and their bit rates as aggressively as possible. This urgency is reflected not so much in today's growth rate of bandwidth demand, which is urgent enough, but even more in the forthcoming explosion in demand that will occur when fiber replaces copper over the *last mile* between the provider's fiber and the user's desktop.

Large businesses have long had leased or owned dark fiber directly between their premises and the fiber of the phone companies — indeed, at the beginning of WDM product deployment in 1995, there was for a very brief period as much WDM product revenue in connecting businesses as in connecting long-haul telco exchanges. This fiber to the business capability is slowly migrating to smaller and smaller businesses.

As for residences, both the telcos and cable providers are steadily moving the fiber-to-copper discontinuity point out toward the premises, as shown in Fig. 5. Phone companies typically deploy some form of digital subscriber loop (DSL), and cable companies deploy cable modems, both characterized by a capacity up to a few megabits per second per user. Ultimately this deployment will produce a fiber termination in the basement of each residence served. From the basement it is but a few short meters of single-mode fiber (perhaps running Gigabit Ethernet or 10GigE) to the desktop, where lives a gigabit per second world inside PCs with numbers like 32-bit bus widths and 1000 MHz clock rates (32 Gb/s).

Today, this desktop gigabit world is kept at arm's length from the other gigabit world of the access, metro, and long-haul interoffice facilities by the primitive nature of the last mile, an affliction for which DSL and cable modems are mere Band-Aids, in this author's opinion. Once this celebrated "last mile" bottleneck (rapidly becoming the "last few tens of meters") is relieved by a fiber to the desktop or wavelength to the desktop connection, one may be sure that imaginative new applications will rapidly develop which the user will find he or she cannot do without. At that point, the rate of increase of bandwidth overload of the entire transport facility will make today's demand growth rates seem relatively tame.

An exacerbating factor in this demand growth situation is that Internet traffic is becoming more symmetrical or *peer-to-peer*, Napster being simply a precursor of the coming situation in which a significant fraction of the attached users act to hub significant traffic themselves.

Perhaps the second most urgent need is some all-optical (or at least totally transparent) way of doing wavelength conversion. Without such components, today either one must have patches of stranded capacity in the form of segments that are unreachable because their particular wavelength is already in use in adjacent segments, or OEO wavelength conversion must be used. The low-cost all-optical wavelength converter problem has been the center of attention for years, but solutions have proved elusive, partly because it has proved difficult to control the action of nonlinear optical devices upon arriving signals that are noisy and have a finite extinction ratio (the zero bit represented by nonzero transmitted power).

A third item on the agenda, one that is not strictly technical, concerns the temptation to interrupt the all-optical lightpath to look at the bits. Traditionally, any node in the network that is handling a significant amount of traffic must be capable of providing the network management operator the exact state of health of each traffic stream passing through it. Many proponents of all-optical networking believe that once each WDM signal is launched at the transmitting node and its ratio of signal to internal laser noise ("relative intensity noise — RIN") is known, not much can happen to it along the lightpath that cannot be deduced by out-of-band lightpath tracer signals and/or the verification of OXC and OADM switch position, plus measurements of OSNR at each node along the lightpath, which can be done fairly nonintrusively by diverting 1 or 2 percent of the signal into suitable instrumentation.

The situation is an exact parallel to that several years ago when Erbium amplifiers replaced OEO regenerators. Before EDFAs it was standard practice to look at the state of health of bits at each regenerator (e.g., using the SONET section byte), but when each WDM EDFA could replace many parallel regenerators (one for each bitstream), and furthermore EDFAs could be spaced farther apart along the path than regenerators, the urgency of looking at the bits receded, and facilities providers accepted telemetry of the pump power level as sufficient for diagnostics. Hopefully the track record of optical-level networking, particularly with respect to the reliability of OXCs, will prove equally convincing, so that history will repeat itself and the necessity for looking at the bits (SONET bytes or things like the so-called digital wrapper, which is somewhat the same thing, but with more bits to play with) will wither away. To be sure, the digital wrapper includes enough spare bits for significant forward error correction, but in a two-layer world where the optical layer is really optical, such questions are properly the domain of the higher end-to-end electronic layer, in this writer's opinion.

A fourth requirement is for enduring and widely adopted standards. The record here is not a brilliant one so far. One would think that, early on, not only would the grid of usable WDM wavelengths have been standardized, which it was, but that agreement would also have been reached on which 8, which 16, which 32, and so forth would be used by all manufacturers, and this didn't happen. It even proved very difficult to get everyone to agree to 1510 nm as the wavelength of the non-traffic-bearing optical supervisory channel.

However, while standardization of optical parameters is proving elusive, standardization of control mechanisms using MPLS for the IP layer and the derivative MPλS for the optical layer seems to be progressing well. Success in this effort will mean not only that the optical layer will interwork well with the IP layer, but that rapid point-and-click provisioning, span and ring protection, mesh restoration, rent-a-wavelength, and other services can be quickly, reliably, and conveniently carried out. What is particularly encouraging is that the telco and IP communities seem to be in reasonable harmony this time, instead of going their separate directions (e.g., proprietary TL-1 messages over SONET/SDH for network control of digital crossconnects, and totally different things like path setup using LDP — label distribution protocol, and OSPF — open shortest path first — for the somewhat analogous control of routers).

Even more encouraging is the very recent work in the Internet Engineering Task Force on "GMPLS" — Generalized Multiprotocol Label Switching. The GMPLS vision aims at providing a common control plane architecture for setting up the swapping of input to output forwarding labels within any kind of node. For IP routers the labels designate principally input and output ports. For optical networks they designate input and output port, and wavelength or band of wavelengths for each OXC. For the time-division world of SONET/SDH ADMs and digital crossconnects, they designate input and output time slots. For some purely space-division switch they designate input and output ports. Thus, GMPLS is a framework that promises unified point-and-click control of packets (including cells), circuits, wavelengths, and ports.

Finally, there is the persistent challenge of component cost reduction. Some feel that the secret is lithography in planar waveguide technology. Others point out that, due to bend radius considerations which are absent with electronics, the analogy with LSI is totally invalid, and cost reductions are better sought without resort to analogies with totally different and therefore irrelevant technology families. This side argues that fiber itself, its micropositioning, splicing, and coupling, are the right place to look. Today, both fiber- and waveguide-based directions are being pursued vigorously. All one can say at this point is that it is a great embarrassment to the photonics fraternity to be unable, in any known branch of the art, to exhibit a cost reduction curve that comes anywhere even close to the Moore's Law curve of electronic LSI. Shame on us.

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Biography

PAUL GREEN (aitchnu@aol.com) retired recently to do telecommunications consulting after many years at MIT Lincoln Laboratory (spread spectrum, adaptive receivers, radar astronomy, seismic arrays), IBM Research (peer networking, optical networking), and Tellabs (optical crossconnects). He has been President of both the IEEE Communications and Information Theory Societies. He is the author of the 1993 textbook *Fiber Optic Networks*. He is a member of the National Academy of Engineering, and recipient of the IEEE Simon Ramo Medal in 1991.