Evolution of Optical Transport Technologies: From SONET/SDH to WDM

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ABSTRACT

It took roughly 10 years for the transport network industry to migrate from PDH to SONET. As this technology swap comes to an end, WDM technology is dawning, promising to revolutionize the network industry, with the possibility of transport bit rates above 10 Gb/s as well as transparency to signal encodings. However, a new wave of equipment upgrade is unlikely to happen as current SONET equipment is just beginning to pay off for its large investment. Thus, in years to come, SONET technology, the current standard for optical fiber access, will have to make room for WDM technology in a gradual way. On its part, WDM equipment must be developed to be backward compatible with SONET technology. This article discusses the requirements and issues involved in making WDM technology interoperable with SONET legacy equipment, as well as the evolution path toward a transparent optical transport network.

INTRODUCTION

Wavelength-division multiplexing (WDM) promises to multiply the bandwidth capacity of optical transmission medium many folds. The principle behind it is the transmission of multiple digital signals using several wavelengths so that there is no interference among them. This effectively allows us to tap the much greater bandwidth capacity of optical fibers.

Digital transmission equipment currently being deployed uses optical fibers to carry a single digital signal per fiber per propagation direction. The most successful and widely spread technology is synchronous optical network/synchronous digital hierarchy (SONET/SDH). Most high-speed digital backbones are SONET/SDH-based.

A natural source of concern is how the new WDM technology is going to interoperate with legacy SONET/SDH equipment. Is WDM technology likely to replace SONET/SDH technology entirely? If so, what is the likely roadmap for this transition to happen? This article tries to foresee answers to these questions, reasoning in terms of both technical arguments and the reality of the network industry. We first present a quick tutorial on SONET/SDH and WDM technologies, presenting their main features. Then we discuss the impact of the emerging WDM technology on SONET/SDH equipment, addressing the various alternatives currently considered for future all-optical WDM networks. Finally, we sketch a roadmap for migration from SONET/SDH to WDM networks.

SONET/SDH TECHNOLOGY

SONET is a standard for optical communication, providing framing, as well as a rate hierarchy and optical parameters for interfaces ranging from 51 Mb/s (OC-1) up to 9.8 Gb/s (OC-192). Initially developed by Bell Communications Research (now Telcordia Technologies), it has been adopted as a standard by the American National Standards Institute (ANSI). A slightly different version, SDH, has been adopted by the International Telecommunication Union — Telecommunication Standardization Sector (ITU-T). Since the discussions in this article are equally applicable to SONET and SDH, we do not make a distinction between the two standards.

SONET was designed to provide a standard access to the optical transmission medium. It uses a specific frame format to carry data plus overhead bytes. SONET channels are synchronous. The synchronization of channels is supported by pointers, which dictate the initial byte position of each channel within the SONET frame. These pointers are used to multiplex digital signals within a single SONET frame efficiently.

SONET has four sublayers: path, line, section, and physical. The path sublayer terminates SONET connections, and is thus responsible for monitoring and tracking the status/performance of connections. The line sublayer is responsible for multiplexing path-layer connections into a single link or fiber, connecting two nodes. Thus, it is also known as the multiplex section sublayer. The line sublayer is also responsible for line protection in the event of a failure. Each link is formed by various sections, which are segments delimited by signal regenerators. The section sublayer, located below the line sublayer, is present at each regenerator and terminal in the network. The physical sublayer provides the transmission of the digital signal over the fibers.

Each of these sublayers has its own overhead bytes in the SONET frame. Of particular importance for this article are bytes D1–D12, as well as bytes K1 and K2. Bytes D1, D2, and D3 form the section data communication channel (DCC),

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which is a channel allocated for data communication between section entities, providing a 192 kb/s communication channel. The channel can be used for alarms, maintenance, control, and monitoring purposes. Bytes K1 and K2 provide the automatic protection switch (APS) function, which protects a line against fiber failures. Bytes D4–D12 provide a 576 kb/s message channel for alarms, maintenance, control, and monitoring of the line.

SONET FRAME STRUCTURE AND INTERFACES

Frame Structure — SONET client signals are encapsulated into the SONET frame in a byte-interleaved format, with a basic frame time of 125 µs. The base signal is the synchronous transport signal level 1 (STS-1). There are overhead and payload data bytes in the 90-byte x 9-row frame structure. The overhead bytes consist of 3 bytes/row. The payload bytes, also called the *synchronous payload envelope* (SPE), consist of the remaining 87 bytes x 9 rows. The resulting STS-1 line speed is 51.84 Mb/s. By squeezing multiple frames into a 125 µs time period, higher SONET signals are obtained. Rather than transmitting multiple frames back to back, these higher-rate signals use a slightly different frame structure, called *concatenated* frames. A concatenated higher-rate frame is formed by grouping all overhead bytes of the various STS-1 frames together in consecutive columns, and then adding the payload columns of each frame afterward so that the transport overhead bytes and payload bytes be grouped.

Interfaces — SONET is designed to operate over a single-mode fiber physical medium. The optical specification of SONET interfaces includes the characteristics of the optical line, as well as the parameters of the optical transmitters and receivers. It also includes the spectral characteristics of the signal, the pulse shape of the transmitter, and the power levels involved at each interface. These specifications ensure interoperability between SONET equipment from different vendors. Moreover, the power level definition of various interfaces is important when budgeting power against fiber lengths, as well as the number and placement of regenerators in a SONET network.

SONET CLIENTS

SONET clients organize their data into SONET signals in various ways. The definition of how the data bytes are arranged within the SONET signal is important because equipment using different methods will fail to communicate. For constant bit rate client signals, the virtual tributary (VT) is used to transport payloads of sub-STS-1 rates. VT1.5 (1.728 Mb/s), VT2 (2.304 Mb/s), VT3 (3.456 Mb/s), and VT6 (6.912 Mb/s) are defined. These VTs are arranged in 3, 4, 6, and 12 columns of the SONET frame, respectively. VT groups are used to carry VTs of various speeds, as long as they all fit into the SONET frame. For instance, a VT group may carry four VT1.5s, three VT2s, two VT3s, and one VT6. Pointers in the SONET frame allow for easy demultiplexing of these sub-STS-1-rate signals.

Although VTs and STS signals can conveniently transport constant bit rate applications, for other emerging applications (e.g., multiplexed voice signals and variable bit rate clients), the allocation of constant rate SONET signals may be wasteful. This is especially true for packet network clients, such as IP and certain asynchronous transfer mode (ATM) traffic classes. These clients are bursty in nature; hence, fixed rate signals would be inappropriate to support them. Therefore, specific schemes for packet transport over SONET have been defined.

ATM over SONET — ATM is a packet switch technology in which 53-byte packets, called *cells*, are switched across an ATM transport network. The term *asynchronous* comes from the fact that ATM does not assign fixed time slots to realize information transfer between two endpoints, as does synchronous transfer mode (STM). ATM makes available an array of transfer services, from constant bit rate (CBR) to variable bit rate (VBR) to unspecified bit rate (UBR).

ATM can run on top of several interfaces. In particular, the ATM Forum has defined SONET interfaces, which involve the mapping of cells into an SPE. Cells are placed back to back, after the cell payload is scrambled by a $1 + X^{43}$ self-synchronous scrambler. This scrambler is in addition to the scrambler used in SONET. The scrambling process is necessary to guarantee that the SONET signal will have enough transitions to allow line rate clock recovery at the receiver.

In order to recover the cells, at the receiver side ATM equipment relies on the ATM header cyclic redundancy check (CRC). Namely, the SPE is scanned, on a sliding 5-byte (ATM header size) window, and CRCs are computed. When a match occurs, synchronization is established, and the scanning stops. The next CRC is checked by jumping 53 bytes ahead, assuming back-to-back cell placement. In case of mismatch, a new synchronization scanning starts.

IP over SONET — IP is another packet network technology, ubiquitously used in computer communication around the globe. Similar to ATM, there are several interfaces over which IP protocols run. IP routers' first access to SONET networks used ATM as an intermediate layer, through Internet Engineering Task Force (IETF) RFC 1483 for IP encapsulation over ATM networks. However, for sake of efficiency, direct access to SONET frames is more attractive for IP. IP over SONET/SDH interface, described in [1], consists of IP/PPP/HDLC over SONET. That is, IP datagrams are encapsulated into Point-to-Point Protocol (PPP) packets. PPP is a protocol that provides link error control and initialization. The PPP-encapsulated datagrams are then framed, using high-level data link control (HDLC), and finally mapped into the SONET SPE. The HDLC framed datagrams are then scrambled, and placed back to back into the SPE, much the same way as ATM cells are arranged.

SONET NETWORKS

SONET networks are typically organized as multiple interconnected rings. The reason for favor-

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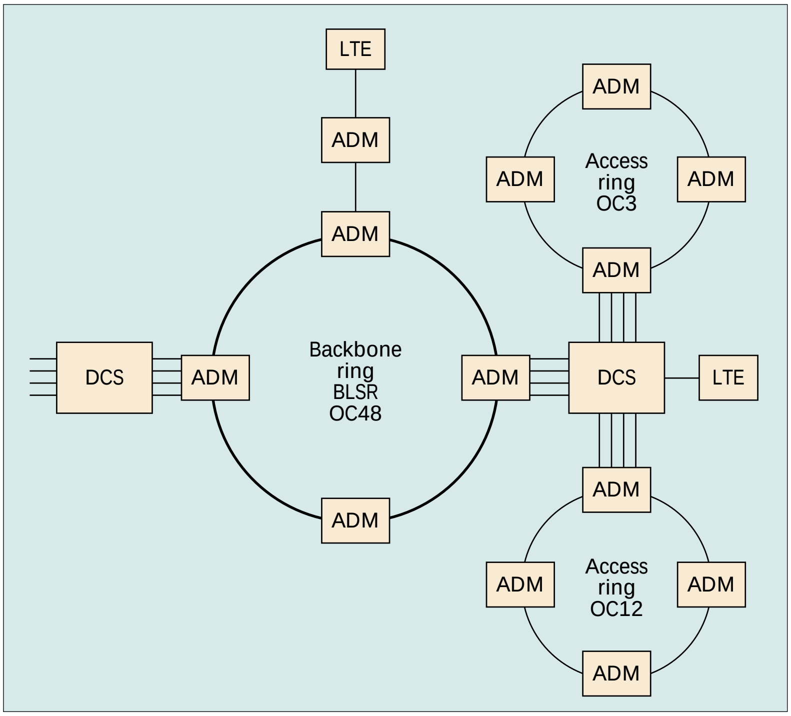

Figure 1. *A SONET network.*

ing ring topology is mainly the APS feature provided by such rings, to be discussed shortly. Obviously, point-to-point links also exist, terminating SONET signals at line terminating equipment (LTE). An example of a SONET network is depicted in Fig. 1.

The figure shows several SONET rings, composed mainly of add/drop multiplexers (ADMs). ADMs are SONET devices which perform low-rate signal grooming into the high-speed SONET signals used in the rings. The rings can be of various speeds, such as OC-3 and OC-12. Depending on the APS provided, they can be unidirectional path-switched rings (UPSRs) and bidirectional line-switched rings (BLSRs), which in turn can make use of a two (BLSR/2) or four (BLSR/4) fiber link span. Digital cross-connect (DCS) devices are used to connect rings together. A DCS cross-connects low-speed signals across rings, providing multiplexing/demultiplexing and switching functions.

THE AUTOMATIC PROTECTION SWITCH

Due to the large bandwidth capacity of fiber optic medium, operations, administration, maintenance, and provisioning (OAM&P) is an important factor. Network administrators must be able to configure paths, monitor their utilization and performance, and take adequate action when necessary. The technology, on the other hand, must provide the means for executing these functions. Thus, some of the SONET/SDH overhead bytes are dedicated to the support of these functions. APS the protocol used for protection of SONET networks against fiber and node failures, is thus one of the most valued features of SONET/SDH equipment. APS provides protection for fiber cuts by automatically redirecting traffic affected by the failure to alternative routes. There are two types of protection mechanisms currently in use: 1+1 and1:1. In 1+1 protection, a SONET signal is transmitted through two nonintersecting fiber paths from a source to a destination. The destination decides which signal to receive based on failure indications provided by the multiplex section sublayer. In 1:1 protection, two nonintersecting paths are also used, with the difference that the SONET signal is transmitted only on one path, called the *working section* (also fiber, or path), while the other path is called the *protection section*. The protection path, idle during normal operation, may be used to transport unprotected traffic, normally called *extra* traffic. The extra traffic is to be stopped when the protection fiber is needed by normal traffic. The process of stopping the extra traffic is called *traffic squelching*.

There are two types of SONET protection rings: multiplex section (MS) dedicated protection rings, and MS shared protection rings. An MS dedicated protection ring is constructed by two counter-rotating rings, transmitting in opposite directions. Only one direction carries normal traffic, while the other is reserved for protection of normal traffic. The dedicated protection ring APS protocol has not been standardized at the time of this writing. Shared protection rings, on the other hand, are realized in two ways: two- and four-fiber shared protection rings. Some of these rings are best known as UPSRs (two fiber) and BLSR/*X*s (X = 2, two; and X = 4, four fibers). The reader is referred to [2] for a more comprehensive description of APS protocols in their various forms.

WDM TECHNOLOGY

WDM is a technology that enables various optical signals to be transmitted by a single fiber. Its principle is essentially the same as frequency-division multiplexing (FDM). That is, several signals are transmitted using different carriers, occupying nonoverlapping parts of a frequency spectrum. In the case of WDM, the spectrum band used is in the region of 1300 or 1500 nm, which are two wavelength windows at which optical fibers have very low signal loss.

Initially, each window was used to transmit a single digital signal. With the advance of optical components, such as distributed feedback (DFB) lasers, erbium-doped fiber amplifiers (EDFAs), and photodetectors, it was soon realized that each transmitting window could in fact be used by several optical signals, each occupying a small fraction of the total wavelength window available. In fact, the number of optical signals multiplexed within a window is limited only by the precision of these components. With current technology, over 100 optical channels can be multiplexed into a single fiber. The technology was then named *dense WDM* (DWDM).

DWDM's main advantage is its potential to cost effectively increase the optical fiber bandwidth many folds. The large network of fibers in existence around the world can suddenly have their capacity multiplied manifold, without the need to lay new fibers, an expensive process. Obviously, new DWDM equipment must be connected to these fibers. Also, optical regenerators might be needed.

The number and frequency of wavelengths to be used is being standardized by the ITU-T. The wavelength set used is important not only for interoperability, but also to avoid destructive interference between optical signals.

WDM COMPONENTS

WDM components are based on various optics principles, outside the scope of this article. Figure 2 depicts a single WDM link. DFB lasers are used as transmitters, one for each wavelength . An optical multiplexer combines these signals into the transmission fiber. Optical amplifiers are used to pump the optical signal power up to compensate for system losses. On the receiver side, optical demultiplexers separate each wavelength, to be delivered to optical receivers at the end of the optical link.

Optical signals are added to the system by optical ADMs (OADMs). These optical devices are equivalent to digital ADMs, grooming and splitting optical signals along the transmission path. OADMs are usually made of arrayed-waveguide gratings(AWG), although other optical technologies, such as fiber Bragg gratings, have also been used.

A key WDM component is the optical switch. This device is capable of switching optical signals from a given input port to a given output port. It is the equivalent of an electronic crossbar. Optical switches enable optical networks to be constructed, so a given optical signal can be routed toward its appropriate destination. Another important optical component is the wavelength converter. A wavelength converter is a device that converts an optical signal coming at a given wavelength into another signal on a different wavelength, maintaining the same digital content. This capability is important for WDM networks, because it provides more flexibility in routing optical signals across the network.

OPTICAL TRANSPORT NETWORKS

WDM networks are constructed by connecting wavelength crossconnect (WXC) nodes in a certain topology of choice. WXCs are realized by wavelength multiplexers and demultiplexers, switches, and wavelength converters. Figure 3 depicts a generic WXC node architecture. Optical signals, multiplexed in the same fiber, arrive at an optical demultiplexer. The signal is decomposed into its several wavelength carriers, and sent to a bank of optical switches. The optical switches route the several wavelength signals into a bank of output multiplexers, where the signals are multiplexed and injected into the outgoing fibers for transmission. Wavelength converters may be used between the optical switch and the output multiplexers in order to provide more routing flexibility. WXCs have been researched for a number of years, although these devices have not yet matured to the point of becoming commercially available at the time of this writing. Among the many difficulties are crosstalk and extinction ratio.

Optical transport networks (OTNs) are WDM networks providing transport services via lightpaths. A lightpath is a high-bandwidth pipe carrying data at up to several gigabits per second.

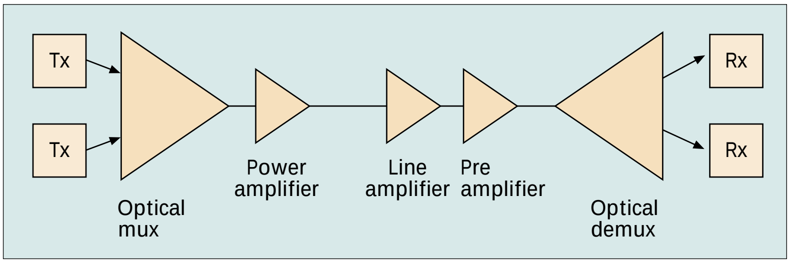

Figure 2. *A WDM link.*

The speed of the lightpath is determined by the technology of the optical components (lasers, optical amplifiers, etc.). Speeds on the order of OC-48 (2488.32 Mb/s) and OC-192 (9953.28 Mb/s) are currently achievable.

An OTN is composed of WXC nodes, plus a management system which controls the setup and teardown of lightpaths through supervisory functions, such as monitoring of optical devices (amplifier, receivers), fault recovery, and so on. The setup and teardown of lightpaths are to be executed over a large timescale, such as hours or even days, given that each of them provides backbone bandwidth capacity.

There is a lot of flexibility in how OTNs are deployed, depending on the transport services to be provided. One of the reasons for this flexibility is that most optical components are transparent to signal encoding. Only at the boundary of the optical layer, where the optical signal needs to be converted back to the electronic domain, does the encoding matter. Thus, transparent optical services to support various legacy electronic network technologies, such as SONET, ATM, IP, and frame relay, running on top of the optical layer, is a likely scenario in the future [3].

The optical layer is further divided into three sublayers: the optical channel layer network, which interfaces with OTN clients, providing optical channels (OChs); the optical multiplex layer network, which multiplexes various channels into a single optical signal; and the optical transmis-

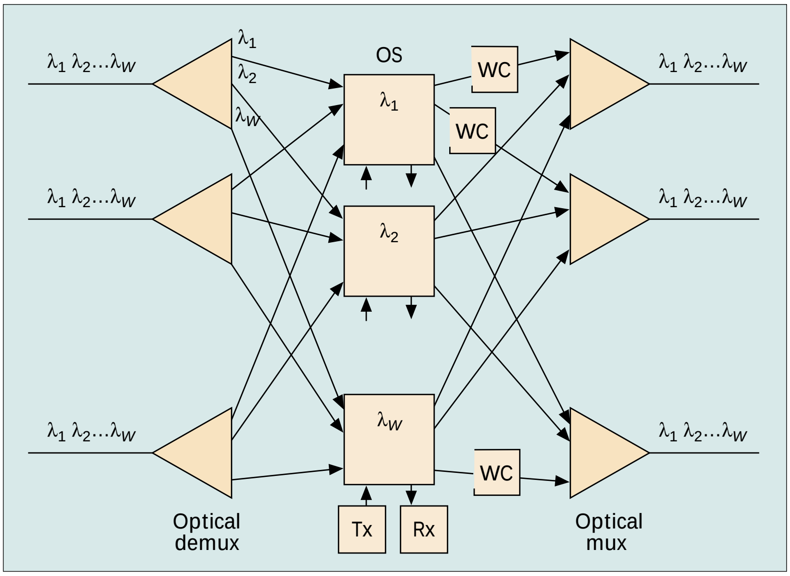

Figure 3. *A wavelength cross-connect node.*

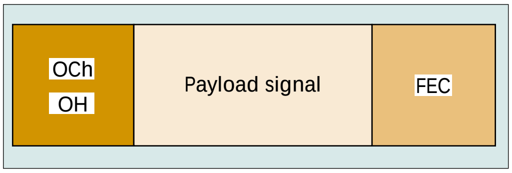

Figure 4. *An optical channel frame.*

sion section layer network, which provides the transmission of the optical signal across the fiber.

OTN FRAME FORMAT

Similar to the use of a SONET frame, access to the OCh is expected to be through an OC frame, which is currently being defined [4]. The basic frame size corresponds to OC-48 speed, or 2488.32 Mb/s, which constitutes the basic OCh signal. Figure 4 depicts a possible OCh frame format.

The leftmost region of the frame is reserved for overhead bytes. These bytes are to be used for OAM&P functions, similar to the overhead bytes of the SONET frame, discussed earlier. However, additional functions are likely to be supported, such as the provision of dark fibers (reservation of a wavelength between two endpoints for a single user) and wavelength-based APS (to be discussed shortly). The rightmost region of the frame is reserved for a forward error correction (FEC) scheme to be exercised on all payload data. An FEC over an optical transmission layer increases the maximum span length, and reduces the number of repeaters. A Reed-Solomon code is expected to be used.

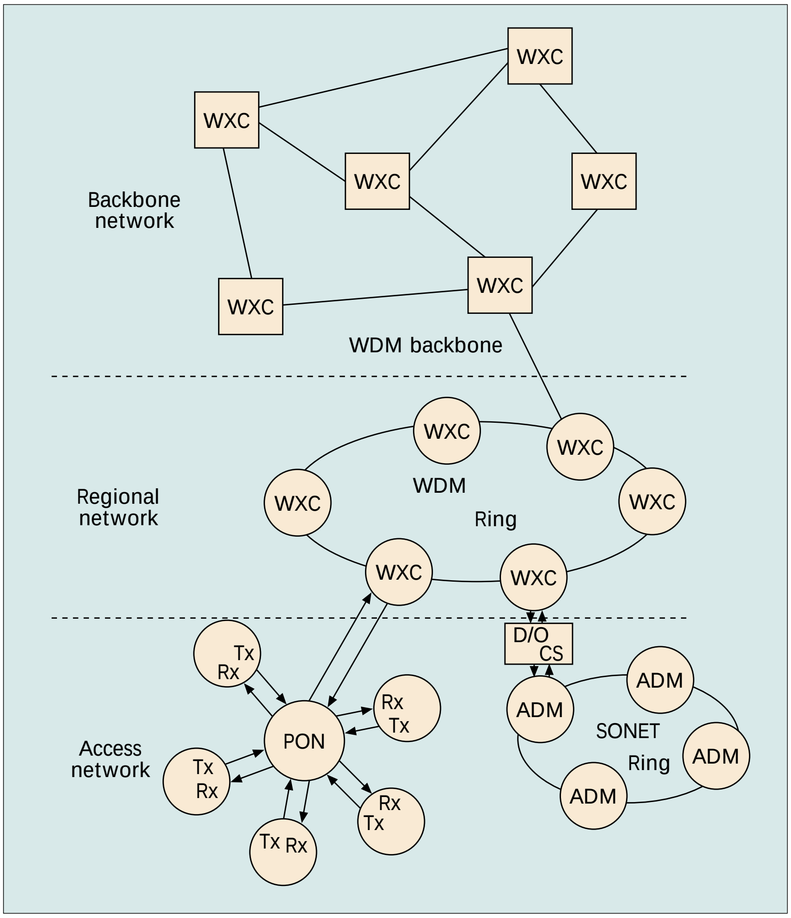

Figure 5. *WDM network infrastructure.*

Several OChs are to be multiplexed together in the optical domain, to form the optical multiplex signal (OMS). This parallels to the multiplexing of several STS-1 frames into an STS-Nc SONET frame format. ITU-T Study Group 15 is working on a draft [4] which addresses, among other issues, the format of the optical frame for both network–network (NNI) and user–network interfaces (UNI). For NNI, OCh rates will be defined so that multiple OChs can easily be multiplexed to form the OMS.

The optical client signal is placed within the OCh payload signal. Notice that the client signal is not constrained by the Och frame format. Instead, the client signal is required to be only a constant bit rate digital signal. Its format is also irrelevant to the optical layer.

WDM RINGS

Conceptually, a WDM ring is not much different from a SONET ring. WXCs are interconnected in a ring topology, similar to SONET ADMs in a SONET ring. The major architectural difference between a SONET ring and a WDM ring is rooted in the WXC capabilities of wavelength switching and conversion. These features can be used, for instance, to provide levels of protection with no parallel in SONET technology. In other words, wavelength or lightpath protection can be provided, in addition to path and line protection.

Various laboratories around the world have been experimenting with WDM rings for a number of years, as documented in recent research literature. Reference [5] identifies at least eight types of WDM rings that are realizable. It is difficult to predict, however, which types of WDM rings will be widely deployed in the future. Regardless of the types chosen, optical APS protocols at least as complex as SONET APSs are necessary. Protection can be provided either at the OCh level or the optical multiplex section/optical transmission section levels. Some extra protection capabilities can be implemented, with no parallel in SONET rings. For instance, a failed lightpath (e.g., a laser failure) can be fixed by converting an optical signal from a given wavelength into a different one, avoiding the rerouting of the signal. This is equivalent to span switching in SONET, with the difference that even two-fiber WDM rings can provide such capability for OCh protection. In the OMS layer, however, span protection will require four fiber rings, as in SONET. These extra features will undoubtedly introduce extra complexity in the optical-layer APS protocols. Reference [2] studied several types of failure-resilient WDM rings. One of the key research opportunities in optical transport systems is the design of APSs for WDM rings.

Once the WDM ring is up, lightpaths need to be established in accordance with the traffic pattern to be supported. This amounts to solving the problem of routing and wavelength assignment. Essentially, the lightpath routes need to be determined, in conjunction with the appropriate assignment of wavelengths in each span of the ring. Signaling protocols are yet to be defined for the management of lightpaths, and should be part of an optical network management platform.

MESH WDM NETWORKS

Mesh WDM networks are constructed with the same optical components as WDM rings. However, the protocols used in mesh networks are different from those used in rings. For instance, protection in mesh networks is a more complex proposition [6], as is the problem of routing and wavelength assignment in WDM mesh networks [7].

Mesh networks are likely to be used as backbone infrastructures connecting WDM rings. Some of these connections are expected to be optical, avoiding optical/electronic bottlenecks and providing transparency. Others will require the conversion of the optical signal into the electronic domain for monitoring, management, and perhaps billing purposes. Figure 5 depicts a WDM network infrastructure.

In the figure we show three topology layers: the access network, the regional network, and the backbone network. We have included both SONET rings and passive optical networks (PONs) as access networks. PONs are networks constructed with passive optical components. They are generally based on a bus or star topology, and a medium access control (MAC) protocol is used to coordinate transmissions among users. No routing functionality is provided in such networks. These architectures are practical for networks supporting at most a few hundred users over short distances. Although PONs are less expensive networks than WDM rings, due to the lack of active components and features such as wavelength routing, the lasers necessary at the PON sources make the first generation of such equipment still more expensive than SONET rings. This favors the SONET solution at the access network level, at least in the near future. If anything, PONs may replace SONET technology at some time in the future as an affordable access network technology. Backbone networks, on the other hand, contain active optical components, hence providing functions such as wavelength conversion and routing.

OPTICAL NETWORKS TESTBEDS

Several initiatives to build WDM backbones are under development. In the United States, we have the MONET project [8], which consists of OADMs or rings interconnected to a long-distance backbone network of optical cross-connects (OXCs). In Europe, a pan-European optical network is being deployed under the Advanced Communications Technologies and Services (ACTS) program [9]. These and other backbone networks will have to somehow interface with legacy transport technologies, such as IP, ATM, public switched telephone network (PSTN), and SONET. The overall scenario is depicted in Fig. 6. Notice the several types of interface involved in the figure.

SONET/SDH AND WDM INTEGRATION

Current network operators are just now finishing the migration from pleisiochronous digital hierarchy (PDH) to SONET/SDH. It took roughly 10 years for this migration to take place. Thus, they are unlikely to embrace any new technology that does not interoperate with SONET/SDH. Many fora are actively working on interoperability issues regarding these two technologies. Among them are the Optical Internetworking Forum (http://www.oiforum.com), the ITU-T Study Group 15 (transport networks, systems, and equipment: http://www.itu.int/ITU-T/com15/index.html), and the Sonet Interoperability Forum (www.atis.org/atis/sif/sifhom.htm). In this section we discuss the requirements and issues for a gradual migration from SONET to WDM networks.

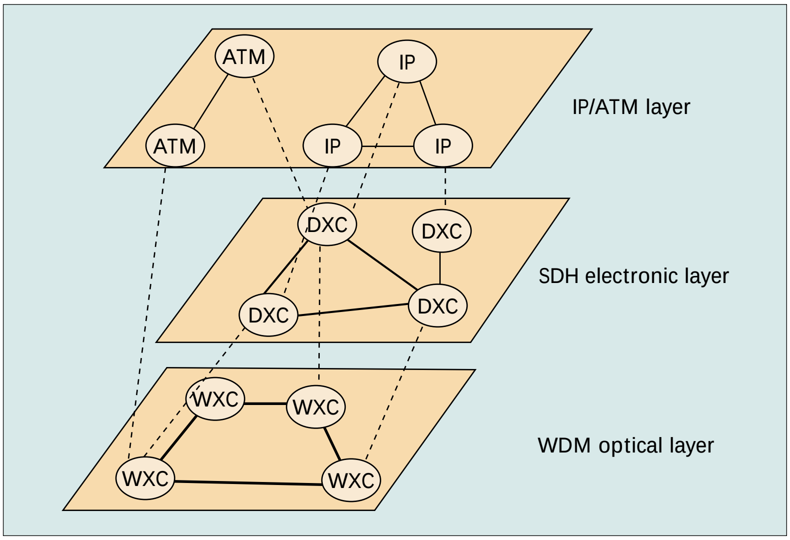

Figure 6. *Overlaying a WDM transport network carrying ATM/IP traffic.*

SONET FRAME ENCAPSULATION

The OCh frame must be defined so that SONET/SDH frame encapsulation can be easily done. The entire STS-48c signal, for instance, has to be carried as an OCh payload. If a basic OC-48 optical channel is used, it might not be possible to encapsulate SONET STS-48c into OC-48, due to the OCh overhead bytes. The OCh frame format is currently being defined. Figure 7 exemplifies SONET frame encapsulation into an OCh frame.

SONET INTERFACES TO WDM

WDM equipment with physical SONET interfaces will deliver optical signals to SONET devices. These interfaces must be in accord with [10] for backward compatibility with SONET technology. Therefore, the SONET device need not be aware of the WDM technology used to transport its signal (e.g., the device can belong to a BLSR/4 ring). In this case, the WXC will drop and add into the optical medium the wavelength originally used in the SONET ring. This way, WDM and SONET layers are completely decoupled, which is necessary for WDM interoperability with SONET legacy equipment. Notice also that this puts extra constraints on the selection of wavelengths in the optical layer, since the last-hop wavelength, the one interfacing with the SONET device, must be the same one used by the SONET device to terminate the optical path, if wavelength conversion is not provided within the SONET device.

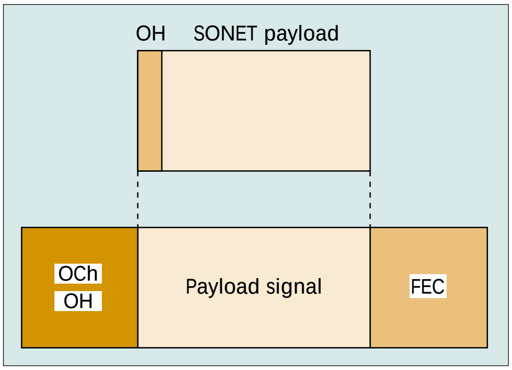

Figure 7. *SONET frame encapsulation.*

THE MULTIPLE-LAYER AUTOMATIC PROTECTION SWITCH

SONET rings have their own APS protocol, described earlier. OChs will also have protection capabilities, since some OCh clients may not possess this capability. Therefore, protection in the OCh layer must be such that it does not adversely interfere with the SONET APS. The optical APS then must react in a timescale faster than SONET can, or quicker than 50 ms, so that recovery is attempted first at the lower OTN layer. In fact, in a multilayer environment, multiple timescale recovery mechanisms must operate in an ascending response timescale. Table 1 lists various recovery mechanisms, with their respective recovery time [11], in a multilayer network.

Notice that although restoration is faster in WDM than in SDH technology, failure detection in WDM is slower. Safer overlay of WDM/SDH protection mechanisms calls for a faster WDM protection scheme. Alternatively, SONET APSs could be artificially slowed down if SONET clients can afford the performance degradation incurred by such procedures. Unnecessary failure recovery at higher layers may cause route instability and traffic congestion; hence, it should be avoided at all costs. Fault persistence checks can be used at higher layers to avoid early reaction to faults at lower layers.

A failure recovery at the OMS sublayer can replace recovery procedures of several instances of the SONET signals being served by the optical layer. Thus, a potentially large number of SONET clients are spared from starting failure recovery procedures at their layers. Therefore, a single failure recovery at the optical OMS sublayer can spare hundreds if not thousands of routing table updates at the IP layer, for instance.

WAVELENGTH PACKING IN SONET AND WDM INTERNETWORKS

The performance and cost of a SONET/WDM integrated network depend on several issues, such as the number of OADMs and topology (ring/mesh). Here we briefly discuss the wavelength packing problem, which has a direct effect on the number of SONET devices to be used. Consider an optical network offering lightpaths between optical/electronic termination points, where OADMs and SONET devices are placed for traffic grooming and delivery. Let's assume basic OC-48(2488.32 Mb/s). Given a traffic matrix, which defines the amount of traffic to be carried between ingress/egress optical termination points, the question is: at the ingress points, how should we populate the various wavelengths with the originating traffic in order to minimize network cost while attending to the transport needs represented by the traffic matrix? In this case network cost can be assumed to be dominated by the number of OADMs and SONET devices. Figure 8 exemplifies the optimization problem.

In the figure, two STS-12 (622 Mb/s) lightpaths are required between optical nodes A and C. If they are packed into the same wavelength, two ADMs are saved. Wavelength packing and routing are current research topics. For instance, [12] studies the wavelength packing problem in WDM rings. Wavelength packing in WDM mesh networks, along with the lightpath routing problem under failures (restoration), is studied in [13].

	Technology	Detection	Restoration	Details
WDM	WDM-OMS/Och	1–10 ms	10–30 ms	Ring/P-P
SONET	SDH	0.1 ms	50 ms	Ring
	APS 1+1	0.1 ms	50 ms	P-P
ATM	FDDI	0.1 ms	10 ms	Ring
	STM	0.1 ms	100 ms	
	ATM PV-C/P 1+1	0.1 ms	10 ms x *N*	Standby *N* = #hops
	ATM PNNI SPV-C/P, SV-C/P	40 s	1–10 s	
IP	Border Gateway Protocol	180 s	10–100 s	
	Interior Gateway Routing Protocol and E-OSPF	40 s	1–10 s	
	Intermediate System-Intermediate System	40 s	1–10 s	
	Routing Internet Protocol	180 s	100 s	

Table 1. *Time responses of various APS mechanisms.*

NETWORK MANAGEMENT

OAM&P procedures are key to the success of any high-capacity transport network. In SONET networks these procedures are proprietary; it is left for each vendor to decide how to implement its network management system (NMS). As a result, SONET devices of distinct vendors do not interoperate. Moreover, these proprietary solutions normally work in isolation from one ring to another, even within the same vendor. This has proven to be a serious drawback in the operation and maintenance of SONET rings.

An OAM&P platform is to be constructed by defining management information blocks (MIBs) for the various optical sublayers. The MIBs must include several types of information, such as physical characteristics (fiber type, maximal rates, wavelength conversion capabilities), protection control, and power levels. They can belong to separate optical sublayers, or include information about various sublayers. Some of the data can be replicated in several MIBs belonging to different sublayers. The exact definition of the MIBs to be used depends heavily on the implementation of the network management platform.

There is an ongoing effort to integrate and manage existing transport networks in a vendor-independent manner [14]. Major telecommunication industries have joined forces to produce a Common Object Request Broker Architecture (CORBA) NMS. The resulting CORBA NMS is to provide an integrated management architecture for various network types, including SONET, WDM, and ATM networks. In the multilayer multitechnology network environment of today, such a network management platform is not only necessary but mandatory.

EVOLUTION TOWARD AN ALL-OPTICAL TRANSPORT NETWORK

Evolution toward an all-optical WDM network is likely to occur gradually. First, WXC devices will be connected to existing fibers (e.g., transatlantic ones). Some extra components might be necessary in the optical link, such as EDFAs, in order to make legacy fiber links suitable to WDM technology. WXCs will interface with legacy equipment, such as SONET and fiber distributed data interface (FDDI). At this stage, the architecture and logical topology of the WDM and SONET layers, discussed in the previous section, are important issues.

Optical subnetworks (possibly rings) will be deployed, interconnected by SDH or ATM equipment. Thus, the optical signal will be brought back into the electronic domain at each interconnection point. This approach allows tight monitoring of failures, such as fiber cuts and laser/detector failures, making feasible the implementation of sophisticated protection mechanisms in the optical layer. New provisioning mechanisms and network management tools need to be developed for this scenario. Several startup companies are currently pursuing this avenue, trying to tap into the DWDM market as early as possible. The downside of this scenario is that a lightpath across WDM subnetworks will not be transparent, in the sense that only SONET encoded signals can be transmitted appropriately.

As SONET devices depreciate, new optical access solutions will appear, squeezing the SONET layer off the protocol stack, together with optical–electronic conversion at intermediate points of a lightpath. This will clear up the lightpaths from electronic–optical conversion, making the optical layer truly transparent. The down side of this scenario is that failure detection becomes a challenging task in a transparent optical layer.

A plus of an all-optical transparent transport network is that the transferring of SONET functions into either the layer above(IP/ATM) or below (WDM) SONET is likely to happen, bringing savings in terms of network upgradability and maintenance. In fact, discussions about new optical access layers, such as packet over OTN, have already started, driven by the rapid advances in WDM technology. To give the reader an idea of the extent to which such layer reorganization could affect transport networks, assume that real-time traffic, including voice, is packetized (IP/ATM). This could lead to the extinction of VTs' SONET signals. A key issue then would be how to most efficiently pack packets into SONET, or even directly into OCh frames. Whatever new encapsulation method emerges, backward compatibility with IP/PPP/HDLC and ATM encapsulation is a must.

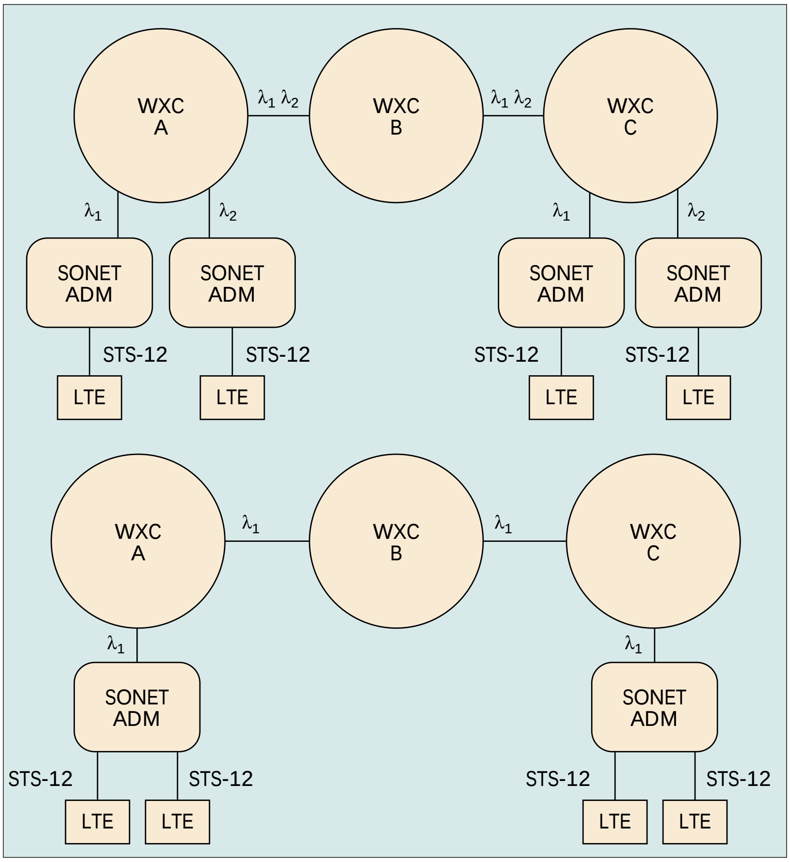

Figure 8. *The wavelength packing problem.*

CONCLUSION

After ten years of SONET/SDH deployment, a vast investment has been made in SONET equipment all over the world. Only in North America did the figure total $4.5 billion in 1998. A slowdown has been detected due to migration of SONET functionalities into ATM and IP equipment, as well as the market growth of DWDM equipment. Figures seem to project a double in DWDM investment in the 1998–2002 period, from $1.86 to $3 billion by 2002 [15]. The emerging WDM technology provides an alternative for fiber access and transport services for the first time. The WDM promises of unlimited bandwidth and fast protection capabilities are not enough to entice network operators to retire their SONET/SDH investment in favor of this new and still unproven technology. The operators are apparently satisfied with SONET technology on

It is clear that a gradual evolution of today's SONET technology into WDM systems is mandatory. The question is how long can this evolution last before it gets hit by the next revolutionizing transport technology, whatever that may be.

both fronts: provision of 50 ms protection capabilities, and speeds up to OC-192 (9.8 Gb/s). The deployment of WDM devices thus must be economically well justified, as well as well planned. In this article we have discussed various issues involved in deploying WDM technology in a SONET-dominated network transport environment.

It is clear that gradual evolution of today's SONET technology into WDM systems is mandatory. The question is how long this evolution can last before it gets hit by the next revolutionizing transport technology, whatever that may be.

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BIOGRAPHY

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