A Practical Vision for Optical Transport Networking

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ABSTRACT

This white paper presents a practical vision for Optical Transport Networks (OTNs). In this vision, OTNs will evolve from point-to-point DWDM remedies to scalable, robust optical-networking applications that cater to a wide variety of client signals having equally-varied service requirements. This paper places the evolution of OTNs in context with other networking trends, and addresses the five factors most central to real-world Optical Transport Networking - span engineering, maintenance, survivability, interoperability, and service transparency. NOTE: A condensed version of this white paper appeared as the introduction to the Bell Labs Technical Journal Special Issue on Optical Networking, Jan.-Feb. 1999.

INTRODUCTION

Commercial lightwave communications over fiber-optic cable began some twenty years ago. Since then, researchers have held a vision of accessing a larger fraction of the theoretical 50 THz of available information bandwidth that single-mode fiber offers. In more recent years, accelerated research has explored sophisticated photonic devices and techniques that would allow the transport and routing of signals in the optical domain. At the same time, network operators, spurred by persistent projections of vastly increased demands for bandwidth for services of widely varying characteristics, have been driven by a vision of a network that could gracefully evolve to meet unknown future demands for increased flexibility, capacity, and reliability. Such networks, in addition to providing high-speed transmission capabilities, would need to incorporate multiplexing and routing techniques appropriate for ultra-broadband services. It was recognized that the efficient implementation of such transmission/switching functions could dramatically reduce overall network cost.

As evidenced by the Special Issue of the Bell Labs Technical Journal on Packet Networking [1], the persistent projections of earlier years have finally become a reality. The current unprecedented demand for network capacity is mostly driven by the rapidly growing demand for packet-based services - in particular, by Internet/Intranet-based applications. A conservative estimate of Internet traffic growth is that it doubles every six months. If this growth rate is accurate, and continues, the aggregate bandwidth required for the Internet by the year 2005 in the US will be in excess of 280 Tbps [2]. Transport networks currently optimized for a mix of narrowband and wideband services (64 kbps to 2 Mbps) must become optimized for much larger channels carrying broadband data, voice, and video. The combination of an unprecedented demand for new capacity and the emergence of very-high bandwidth applications, at a time when many network service providers are experiencing high utilization rates of their existing fibers, has led network planners to look for the most expedient and cost-effective means of increasing capacity.

Hence, the research vision of virtually infinite information bandwidth and transport in the optical domain, together with network operator needs for dramatically increased network capacity and an
associated broadband infrastructure, have become mutually reinforcing thrusts. With individual channels in the transport network growing to gigabits/second, and with optical technology becoming increasingly viable and cost-effective, we are now witnessing rapid large-scale deployment of Wavelength Division Multiplexed (WDM) systems worldwide. Network operators are relying on WDM extensively to expand transmission capacity on long-haul and fiber-limited routes, currently achieving throughput in excess of 400 Gbps per fiber. Because the primary short-term need being addressed has been capacity gain, these deployed systems have been point-to-point line systems. Beyond these point-to-point WDM applications, the next evolutionary step in reliable, scalable transport networks will be optical networking.

But what exactly is optical networking? Like many other networking techniques, optical networking implements functionality for transmission, multiplexing, routing, supervision, and survivability for a wide range of client signals. As described in a previous issue of the Bell Labs Technical Journal [3], optical networking operates predominantly in the optical domain, where the unit of bandwidth granularity – the optical channel – is much larger than in Time Division Multiplexed (TDM) networks. In an optical network, the optical channel ("frequency slot") may be considered as analogous to a time slot in a TDM system, with optical-network elements manipulating optical channels ("frequency slots") similar to the way TDM elements manipulate time slots.

In an idealized optical network, there are no analog engineering constraints on optical-channel routing; the network is completely service-transparent, that is, free from service-specific functions that can limit flexibility. In addition, ubiquitous wavelength conversion (interchange) is available to minimize stranded capacity, and there is support for a multi-vendor environment. Of course, the reality is more challenging. Public telecommunications relies on an extremely diverse network of networks, with widely varying topologies, deployed technologies, services, and underlying business models. A practical vision for optical networking is one that goes beyond point-to-point WDM transmission to address the practical needs of this diverse networking environment. It encompasses the progression of applications from long-haul capacity expansions toward a unified end-to-end optical network, spanning access, metro, and long-haul domains. Such a vision also describes how optical networking supports an expanding variety of client signals that have equally varied service requirements – flexibility, scalability, and survivability, coupled with bit-rate and protocol independence.

This paper focuses specifically on optical-networking solutions for transport applications², or the Optical Transport Network (OTN). Optical techniques have been evolving for a wide range of networking applications. However, owing to the unique combination of technology and business forces, it is on transport networks specifically that optical networking offers the most immediate and extensive payoffs. While much of this paper is relevant to the full range of optical-networking applications, including enterprise and residential access, it specifically addresses transport applications.

In summary, optical transport networking has come of age. A practical vision for optical transport networks – one that is widely deployable, highly reliable and maintainable, readily evolvable, and demonstrably cost-effective – is now at hand. This paper lays out this practical vision, placing it in context with other networking trends. In addition, this paper addresses the most critical factors to consider in architecting optical transport networks.

OPTICAL TRANSPORT NETWORKING

It is essential to clearly define what is meant by the term Optical Transport Networking. After all, the ability to support optical transmission is not new – SONET/SDH equipment has been used successfully in the construction of single-channel optical transmission systems for some time. However, SONET/SDH networks and optical networks differ in several respects; in particular, in how they support capacity expansion and channel routing. In SONET/SDH networks, once the transmission rate of a network’s single optical channel has been maximized, capacity expansion

² Transport networks provide the underlying high-capacity infrastructure for core interoffice, metropolitan interoffice, and broadband business-access networks. We distinguish these transport-networking applications from other applications, such as residential access and enterprise networking, because each may have quite different architecture requirements for capacity, traffic management, physical topologies, operations, and reliability. At the same time, there may also be some technologies and other aspects that are common across all these applications.
involves adding new transmission systems in parallel over separate fibers. In optical networks, capacity expansion involves simply adding wavelengths within the same fiber (up to some predefined maximum) and transmission system. The routing functions for SONET/SDH networks are performed by means of time slots, whereas the routing functions for optical networks are performed by means of optical channels (frequency slots) between wavelengths of various frequencies.

The use of WDM – more specifically, the rapid deployment of point-to-point WDM line systems in telecommunications networks worldwide – is viewed as the first step toward optical transport networking. While WDM line systems alone support little in terms of networking functionality, the elements for WDM optical transport networking are on the horizon. WDM line systems with fixed wavelength add/drop capability are being deployed, and optical-network elements with nodal features, such as optical add/drop multiplexers (OADMs) and optical cross-connects (OXCs) – employing either electrical or optical switching matrices – have been reported to be in laboratory and field trials. The ability of these WDM nodal elements to add, drop, and in effect construct optical channel-routed networks allows for the manipulation of optical channels in WDM networks, just as time slots are manipulated in TDM networks today (see Figure 1).

Optical transport networking is defined as the ability to construct WDM networks having advanced features, such as optical-channel routing and switching, that support flexible, scalable, and reliable transport of a wide variety of client signals at unprecedented bandwidth granularities – upwards of tens of Gbps per optical channel.

**NEXT GENERATION NETWORKS**

This section introduces how our practical vision of optical transport networking relates to Lucent’s vision of the next generation network, as presented in the Bell Labs Technical Journal Special Issue on Packet Networking [1]. We first summarize the role of optical transport networking in the next generation network, and then examine the evolution of transport networks from single-wavelength TDM networks to WDM line systems, and ultimately to the vision of optical transport networking at the optical-channel level.

**OPTICAL TRANSPORT NETWORKING IN THE NEXT GENERATION NETWORK**

Today’s TDM-based transport networks have been designed to provide an assured level of performance and reliability for predominantly voice and leased-line services. Proven technologies, such as SONET/SDH, have been widely deployed in the current transport infrastructure, providing high-capacity transport, scalable to gigabit-per-second rates, with excellent jitter, wander, and error performance for 64 kbps voice connections and leased-line applications. SONET/SDH self-healing rings enable service-level recovery within tens of milliseconds following network failures. All of these features are supported by well-established global standards, enabling a high degree of multi-vendor interoperability. To summarize, SONET/SDH has been the transport-networking technology of choice for a world dominated by circuit-voice and leased-line services.
In contrast with today’s TDM-based transport networks – and, to some extent, with ATM networks – legacy “best-effort” IP networks generally lack the means to guarantee high reliability and predictable performance. The best-effort service provided by most legacy data networks, with unpredictable delay, jitter, and packet loss, is the price paid to achieve maximum link utilization through statistical multiplexing. Link utilization (for example, the number of users per unit of bandwidth) has been an important figure of merit for data networks, because the links are usually carried on leased circuits through the TDM transport network. While today’s data networks provide excellent connectivity, they do not enable controllable distribution of network resources among traffic from competing users. Given the inherently bursty statistics of packet data traffic, the fixed bandwidth pipes of TDM transport may not be an ideally efficient solution. However, this inefficiency has traditionally been considered of less importance than the network reliability and congestion-isolation features that a TDM-based transport network provides.

The surging demand for high-bandwidth and differentiated data services is now challenging this dual-architecture model of TDM-based transport and best-effort packet data networks. It is not cost-effective to extend the usefulness of best-effort networking by over-provisioning network bandwidth and keeping the network lightly loaded. Further, this approach cannot always be achieved or guaranteed due to spotty demand growth, and is a particular issue for the network access domain that is most sensitive to economic constraints of under-used facilities. For a commercial network, an additional drawback of the best-effort model is that the network relies only on user (customer) cooperation for congestion control, by assuming that end users will slow down their transmission rates when significant congestion is detected. As a result, in general, data-service providers today do not have the network infrastructure support to provide customer-specific, differentiated-service guarantees and corresponding service-level agreements.

With regard to satisfying these new network requirements, the Bell Labs Technical Journal Special Issue on Packet Networking [1] described a new data-centric optical transport network architecture. This next generation network will dramatically increase, and maximally share, backbone network-infrastructure capacity, and provide sophisticated service differentiation for emerging data applications. Complementing the many service-layer enhancements, optical transport networking will provide a unified, optimized layer of high-capacity, high-reliability bandwidth management, and create “Optical Data Networking” solutions for higher-capacity data services, with guaranteed quality.

**The Value of Transport Networking in a Data-Centric World**

Network architectures for cost-effective, reliable, and scalable evolution employ both transport networking and enhanced service layers, working together in a complementary and interoperable fashion. Transport networking, whether based on SONET/SDH or optical technology, enables the service layers to operate more effectively, freeing them from constraints of physical topology to focus on the sufficiently large challenge of meeting service requirements. This point is fundamental to an understanding of our vision of optical networking.

Transport networking offers four primary benefits:

- It is the only solution for fast survivability, and it supports service-layer restoration with efficient shared-protection architectures.
- It enables service-layer scalability, controlling the pace of service-layer upgrades by freeing the service-layer logical topology from the network’s physical-link topology.
- It enables you to achieve a lower-cost network, especially when upgrade-fueled lifecycle costs are included.
- It establishes a future-ready unifying infrastructure for efficient multi-service networking in an unpredictable service environment.

These benefits are apparent when considering the cost and functionality of intermediate nodes along high-capacity, long-haul service routes. As shown in Figure 2, transport networking permits a flexible, cost-effective end-to-end connection without incurring the cost of service-layer processing at the intermediate nodes. As traffic demand grows, the transport network evolves from managing broadband circuits toward managing optical channels.
However, what if optical transport never progresses beyond point-to-point WDM interconnects between service-layer elements? Point-to-point transport, rather than full-functionality transport networking, places new demands on the service layer for through-traffic networking and survivability, on top of the rapidly growing service layer requirements. Already, growth and churn are forcing many data-networking systems to be replaced or upgraded every 12 to 18 months. Analysis of real networks suggests that without the support of transport networking, the aggregate service-layer capacity more than doubles in order to compensate, and likely shortens useful service-layer lifecycles even further.

Thus, even in emerging broadband data-networking applications, a full-functionality transport layer provides considerable value. From an optical transport networking perspective, the essential elements are efficient and cost-effective capacity expansion, flexible optical-channel bandwidth management, and survivability mechanisms to support improved reliability of data networks.

**Transport Capacity Expansion**

As discussed earlier, the combination of an unprecedented demand for new capacity and maximal usage of existing cable systems has led network planners to look for the most expedient and cost-effective means to increase capacity. Thus, embedded carriers must evolve their current transport architectures, currently optimized for a mix of narrowband and wideband services (64 kbps to 2 Mbps), to become optimized for larger-capacity channels carrying broadband data, voice, and video. WDM’s increasingly high channel counts and large information capacity are an excellent solution to these needs.

**Optical Channel Bandwidth Management**

Bandwidth management functions – routing channels through a network using add/drop, cross-connect, and interchange techniques – are essential for real networks, because they provide an efficient means to accommodate growth and churn. Several levels of bandwidth-management granularity are necessary, reflecting a range of service requirements and the increasing degree of traffic aggregation toward the core of the network. While the explosion in data traffic is driving enhanced requirements for fine-granularity bandwidth management in the IP and ATM service layers, it is simultaneously creating a rapid proliferation of ultra-broadband optical channels. Optical transport networking will provide flexible management for these optical channels, complementing SONET/SDH’s bandwidth management for lower-bandwidth transport channels.

**Network Reliability**

How will next generation networks deliver data services with the reliability of today’s voice network? While service-layer enhancements will improve packet loss and delay, transport-network survivability provides the best first line of defense against major network faults. Survivable transport networks are essential for two reasons – fastest recovery from faults such as fiber cuts, and efficient capacity utilization through shared-protection mechanisms. For broadband data networks, recovery time becomes even more critical as each fiber span carries an ever-increasing amount of information. Transport protection-switch times, on the order of tens to hundreds of milliseconds, are orders of magnitude faster than for typical service-layer scheme, giving multi-service providers important options to meet premium Service Level Agreements. In addition to delivering the fastest recovery from faults, the next generation network will include advances in survivable network efficiency and flexibility. The survivable optical network will be able to optimize the use of

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For a more complete treatment of bandwidth management, see [4].
protection bandwidth, as well service routing, on an optical-channel basis.

**LEGACY TRANSPORT NETWORK EVOLUTION**

WDM is a revolutionary technology in many respects. However, its impact on transport networking is largely evolutionary, leading to the next phase of capacity expansion and service independence. From a high-level architectural perspective, optical transport networks will follow many of the same architectural principles as their SONET/SDH predecessors. Therefore, a basic understanding of SONET/SDH transport networking (Figure 3) is essential to understanding the nature of practical optical transport networks.

A decade of SONET/SDH deployment has established several types of network elements and network topologies as the basis for transport networking. There are three broad classes of network elements: multiplexers, including Terminal Multiplexers (TMs) and Add/Drop Multiplexers (ADMs); regenerators; and Digital Cross-connect Systems (DCSs). Among numerous network topologies, survivable rings have proven to be particularly useful.

A ring comprises a set of ADMs that allow traffic to enter and exit the ring, interconnected in a loop configuration. The main advantage of the ring topology is protection; the ring offers traffic two different ways of passing from ingress to egress. To satisfy varied requirements, there are several ring-based protection schemes, including SONET 2-fiber and 4-fiber Bi-directional Line Switched Rings (equivalent to SDH Multiplex Section Shared Protection Rings) and SONET Unidirectional Path Switched Rings (akin to SDH 1+1 Sub-Network Connection Protection in a physical ring). For long-span applications, regenerators can be placed at approximately 40 - 80 km spacing between ADM nodes. Rings may also exist in open configurations (linear add/drop, open ring). Or, in the simplest form of ring, the ADM can be configured in a point-to-point configuration (for example, 1+1 SDH Multiplex Section Protection/SONET Line Protection).

Digital Cross-connect Systems groom traffic at various rates to ensure that network facilities are well used, and are key elements in mesh-based restoration architectures. In a typical application, low-speed signals dropped from an ADM are routed through a digital cross-connect system, where they may be groomed (that is, separated and recombined according to service type or destination), and handed off to another ADM. Traditionally, cross-connect systems have not performed the ring facility termination functions associated with ADMs (for example, Multiplex Section protection switching), although Lucent Technologies' next-generation transport system, along with the advancements in technology, have changed this paradigm.

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**Figure 3. SONET Transport Network Architectures**
the WaveStar™ BandWidth Manager, integrates this functionality and eliminates standalone ADMs.

ADMs and regenerators are most often deployed in single-vendor configurations for management and interworking simplification. On the other hand, DCS systems must support more extensive multi-vendor inter-working, because they serve a “hub” role in a central office, terminating electrical and optical signals from the multi-vendor network.

It should be noted that the variety of survivability architectures deployed within inter-office and long-haul backbone networks, as well as within access transport networks, reflects the critical need for high networking reliability and performance. Along with the dramatic increase in network capacity that has taken place over the last decade, customers have been concerned with such issues as: surviving catastrophic failures in cable-facility and equipment sites; the restoration times of critical circuits when a wire center failure occurs; and new survivability levels for applications such as automatic teller machines, local area network interconnection, and mainframe-to-mainframe computer links.

From the perspective of evolving to optical networking, many SONET/SDH transport functions and architecture principles will transfer to new optical transport networks as the basic unit of transport bandwidth shifts from time slot to optical channel (frequency slot).

**THE NEXT PHASE: POINT-TO-POINT WDM**

Point-to-point WDM represents the next phase in the evolution of transport networking, and the first realization of optical networks based on multiple wavelengths. WDM deployment is growing rapidly because it is often a more cost-effective way to expand capacity than any alternatives, such as adding fiber or replacing current-capacity (for example, 2.5 Gbps) Time Division Multiplexing (TDM) transport systems with new, higher-rate TDM systems. New fiber is particularly expensive for long routes, and its installation can take too long to satisfy some customers. Upgrading TDM systems often turns into wholesale replacement, and TDM technology is no longer keeping pace with the emerging ultra-broadband data backbone demands.

Compared to new fiber or upgraded TDM systems, point-to-point WDM systems (Figure 4) offer a superior value proposition, in particular for the long-distance environment, where electronic regenerators are required for long, “repeated” transmission spans.

This value proposition is based on the following:

- **High-capacity path routing:** the high TDM capacity per optical channel (frequency slot) allows “direct feed” from IP routers and ATM switches with ultra-broadband interfaces.
- **Electronic regenerator cost savings:** for an N-channel system, a single Optical Amplifier (OA) replaces N electronic regenerators at each
repeater site.

- **Greater transport capacity per fiber**: the addition of WDM Terminal Multiplexers (WDM-TMs) exploits the inherent capacity of optical fiber, which is vastly underused by single-channel optical transmission systems.

- **Preservation of investment in existing equipment**: existing TDM equipment need not be replaced, but continues to operate in parallel with other, new TDM equipment on the same fiber.

- **Unification of transport for all services**: different types of services, both existing and new, can use the same fiber, virtually independent of bit rate or protocol.

In short, WDM allows service providers to tap into the full capacity of their existing fiber plant, thus maximizing the return on existing facilities. In addition, the service provider has the flexibility of adding new services onto the existing fiber to accommodate new capacity demands.

As illustrated in Figure 4, point-to-point WDM can be deployed on individual spans of a TDM ring topology, as well as on linear networks. In either case, the existing TDM network continues to operate as if it were still the only application on the fiber (for example, TDM protection is still active), and new applications can be added to new wavelengths without impacting the existing TDM traffic.

Several fundamental technology advances, particularly dispersion-managed fibers coupled with Erbium Doped Fiber Amplifiers (EDFAs), have helped make WDM a cost-effective, deployable technology. Commercially available WDM systems carry 16 or more wavelengths, each capable of carrying up to a 2.5-Gbps or 10-Gbps signal. Further, the rapid pace of WDM-related technology advances has resulted in the announcement of higher and higher channel-count systems. For example, Lucent Technologies recently unveiled an 80-channel, global optical networking system, the WaveStar™ OLS 400G, delivering up to 400 Gbps on a single fiber. Other advances, such as Lucent Technologies AllWave™ fiber, are opening up previously unusable parts of the optical spectrum for WDM transport, permitting even more wavelengths on each fiber.

WDM represents the first step toward optical networking, because it employs wavelength-based transport. However, in these initial point-to-point applications, most of the transport-networking functionality is provided by the underlying TDM systems that use the WDM span. As network traffic grows and WDM deployment continues, optical channels will increasingly become the fundamental medium for exchange in networks. Transport-networking functions will migrate into the optical layer, and carriers will begin to manage capacity at the optical-channel level. Consequently, the application of WDM in the transport network will quickly evolve from point-to-point capacity expansion to scalable and robust optical transport networking applications that cater to an expanding variety of client signals with equally varied service requirements.

**THE FUTURE: OPTICAL TRANSPORT NETWORK EVOLUTION**

As previously indicated, Optical Transport Networking (OTN) represents a natural next step in the evolution of transport networking. As an evolutionary result, optical transport networks will follow many of the same high-level architectural principles as followed by SONET/SDH transport networks. For instance, both SONET/SDH and OTN are connection-oriented, multiplexed networks. Thus, optical-network topologies and survivability schemes will closely resemble – if not mirror – those of SONET/SDH TDM networks.

At the same time, there are some important, if subtle, distinctions between optical and SONET/SDH networks. The major differences derive from the particular form of “multiplexing” technology used: digital Time Division Multiplexing for SONET/SDH versus analog Wavelength Division Multiplexing for OTN. The digital versus analog distinction turns out to have a profound effect on the fundamental cost/performance trade-offs in many aspects of OTN network and system design. In particular, the complexities associated with analog network engineering and maintenance implications, as outlined in Section 4, account for the majority of the challenges associated with optical transport networking.

To satisfy the short-term need for capacity gain, large-scale deployment of WDM point-to-point line systems will continue. As the number of wavelengths grows, and as the distance between terminals grows, there will be an increasing need
to add and/or drop wavelengths at intermediate sites. Hence, flexible, reconfigurable optical add/drop multiplexers (OADMs) will become integral elements of WDM networks. As more wavelengths become deployed in carrier networks, there will be an increased need to manage capacity, as well as to hand off signals between networks, at the optical-channel level. In much the same way that digital cross-connects emerged to manage capacity at the electrical layer, optical cross-connects (OXCs) will emerge to manage capacity at the optical layer. Similar to their electrical counterparts, OXCs will be required to support a multi-vendor environment, while individual linear and ring subnetworks based on optical line system (OLS) terminals and OADMs will typically be single-vendor.

Figure 5 depicts an optical transport network for core, metro-interoffice, and high-capacity business-access applications. Initially, the need for optical-layer bandwidth management will be most acute in the core (long distance) environment. The logical mesh-based connectivity found in the core will be supported by way of physical topologies, including OADM-based shared protection rings, and OXC-based mesh restoration architectures, depending on the service provider's desired degree of bandwidth "overbuild" and survivability time-scale requirements. As similar bandwidth-management requirements emerge for the metropolitan interoffice (IOF) and Access environments, so too will OADM ring-based solutions optimized for these applications: optical shared protection rings for mesh demands, and optical dedicated protection rings for hubbed demands.

Hence, just as the optical amplifier (OA) was the technology enabler for the emergence of WDM point-to-point line systems, in turn, OADMs and OXCs will be the enablers for the emergence of the optical transport network. The optical layer will come to serve as the unifying transport infrastructure for both legacy and converged packet networks. Of course, service-provider movement to optical transport networking will be predicated on the transfer of the required transport-networking functionality to the optical layer, concurrent with the development of an OTN maintenance philosophy and associated network-maintenance features. This leads us to the key factors associated with realizing the vision of optical transport networking.

**BUILDING A NEW TRANSPORT LAYER: A PRACTICAL VISION FOR OPTICAL TRANSPORT NETWORKING**

Realizing optical transport networking architectures involves carefully balancing a web of tradeoffs in context with a set of critical factors, and successfully rising to meet associated technical and networking challenges. Implicit in the balancing exercise is the ubiquitous
cost/functionality tradeoff - in other words, at what price functionality? Rather than a single solution for all applications, a range of optical-networking architectures will arise as each market segment applies its unique priorities to make fundamental architecture tradeoffs. In considering the key issues and cost/functionality trade-offs for next-generation optical transport networks, five critical factors emerge:

- **Analog network engineering**: In order to assure a high-performance network, it is necessary to limit the accumulation of analog impairments, while balancing cost with other tradeoffs. A network-engineering strategy that enforces network integrity at subnetwork domain boundaries, resulting in a segmented approach to span engineering and regeneration, will help realize this goal.

- **Service Transparency**: In order to future-proof the network, and to simplify the engineering of the shared multi-service core, a strategy is needed to minimize the amount of client-dependent processing within the core of the optical transport network.

- **Survivability**: While continuing to offer the fastest possible recovery from faults, a strategy is needed to ensure that the next-generation transport network continues to offer a high degree of survivability coupled with network efficiency and service flexibility.

- **Maintenance**: An essential element to realizing cost and service transparency goals is a maintenance philosophy tailored to the unique needs and constraints of optical transport networking. This OTN maintenance philosophy should build on prior experience with TDM and FDM systems, incorporating useful features, while avoiding the mistakes of the past.

- **Interoperability**: As standards and underlying technologies mature, near- and mid-term evolutionary strategies are required to help ensure a smooth transition from single-vendor solutions to multi-vendor, interoperable optical transport networks.

**ANALOG NETWORK ENGINEERING**

Despite the apparent similarity between SONET/SDH and optical-networking architectures, the difference in design and implementation of these transport networks is fundamental. While the former is an exercise in digital network engineering, the latter is an exercise in analog network engineering, somewhat similar to the design of frequency division multiplexed (FDM) networks of old. The chief advantage of digital transmission has been the ruggedness of the digital signal. The limiting factor in a properly designed digital system is not impairments introduced by the transmission facility, but rather the accuracy of the conversion of the original analog waveform into digital form. A major advantage has been that system noise is controlled by the design of the digital network element and is essentially independent of the total length of the system. Because no appreciable degradation is incurred in time division multiplexing or demultiplexing, facility arrangements do not typically need to take the number of previous multiplex/demultiplex operations into account. In contrast to TDM systems, the phase distortion and attenuation (and resulting noise degradation) suffered by channels at the band edge of FDM systems can affect the system performance and so must be explicitly considered in engineering the total system [5]. In the excitement associated with advances in optical-networking technology, the implications of the differences cited above have not always been sufficiently considered.

In what is termed “all-optical” networking, signals traverse the network entirely in the optical domain, with no form of opto-electronic processing within optical-network elements. This implies that all signal processing – including signal regeneration, routing, and frequency slot interchange (FSI), or wavelength interchange – takes place entirely in the optical domain. Over recent years, there has been considerable debate over the nature of the term “optical” in optical networking: in retrospect, it is clear that function and implementation were often confused. Given analog engineering constraints, and considering the current state-of-the-art in all-optical processing technology, the global, or even national, “all-optical” network is not attainable. In particular, opto-electronic conversion may be required in optical network elements to prevent the accumulation of transmission impairments – impairments that result from such factors as fiber chromatic dispersion and non-linearity’s, cascading of non-ideal flat-gain amplifiers, optical signal crosstalk, and transmission-spectrum-narrowing from cascaded non-flat filters [6]. Opto-electronic conversion can also support wavelength interchange, which is...
currently a challenging feature to realize in the all-optical domain. In short, in the absence of commercially available devices that perform signal regeneration to mitigate impairment accumulation and support wavelength conversion in the all-optical domain, some measure of opto-electronic conversion should be expected in practical optical-networking architectures. Because the use of opto-electronics is often associated with higher-cost solutions, the ensuing exercise in cost reduction involves establishing what constitutes the minimum required amount of opto-electronics necessary to assure the presence of desired optical transport networking attributes enabled by their presence. In the near term, the result of this exercise is reflected in optical-networking architectures characterized by transparent (or “all-optical”) segments, bounded by opto-electronics, as shown in Figure 6.

Until standards for the OTN – which are in the early stages of development [7] – are fully developed, the near-term transparent subnetworks shown in Figure 6 will likely remain single-vendor solutions. Hence OXC, as points of multi-vendor interoperability, are shown distinct from near-term, single-vendor OADM and OLS-based subnetworks. The emergence of OTN standards will change this view, as described below.

Figure 6. Practical Optical Transport Networking Architectures

SERVICE TRANSPARENCY

As we have seen in the preceding discussion, practical considerations will govern the ultimate realization of the Optical Transport Network (OTN). Paramount among these considerations is the network operator’s desire for a high degree of service transparency within the future transport infrastructure. As the term “transparency” has tended to engender much discussion, we will attempt here to clearly define the intent of the term “service transparency”.

SONET/SDH offers a good example of service transparency. Specifically, for a desired set of client signals targeted for transport on a SONET/SDH network, individual mappings are defined for carrying these signals as payloads of SONET/SDH server signals (along with associated SONET/SDH overhead to assure proper networking functionality). Once a client signal has been mapped into its SONET/SDH server signal at the ingress of the SONET/SDH network, an operator deploying such a network need not possess detailed knowledge of the client signal until it is de-mapped at the network egress. This definition of service transparency is equally applicable to the OTN. Indeed, once a client signal is mapped into an optical channel, an OTN network operator should not require detailed knowledge of (nor access to) the client signal until it is de-mapped at the OTN egress. Hence, the optical-network ingress and egress points should delimit the domain of OTN service transparency.
Service transparency is an essential factor, because it helps control the complexity of the optical network's role as a unifying infrastructure for all types of clients. In the context of optical transport networking, the notion of service transparency is currently limited to digital client signals, but the scope will ultimately expand to include analog client signals as well. Without service transparency, one must be aware of the type of client signal on every channel throughout the network, resulting in increased network engineering and maintenance complexity. The most important factor in realizing service transparency is to eliminate all client-specific equipment and processing between OTN ingress and egress points. Fortunately, at the ingress/egress point, it is easier to accept client-dependent equipment, because it is generally dedicated on a per-service basis anyway. For example, we might expect different opto-electronic port units to be required to support a mix of 622 M bps, 2.5 Gbps, and 10 Gbps SDH/SONET; Gigabit Ethernet; emerging IP/WDM mappings; and leased “clear-channel” optical channels. Thus, service transparency within the OTN minimally requires flexibility at the optical-channel layer to carry a wide variety of digital client signals.

We will now examine the impact, and consequent implications, on service transparency of deploying optical-network architectures characterized by optically transparent segments bounded by opto-electronic processing. One immediate engineering consequence of such an architecture is that cascading opto-electronic processing units will introduce digital jitter and wander accumulation within digital client signals carried on optical channels, unless they employ so-called 3R regeneration to regenerate, reshape, and retime these client signals. By virtue of this re-timing functionality, such devices have traditionally depended on the client-signal bit rate. However, bit-rate dependent opto-electronics result in constraining the service transparency of optical networks. The use of “broad-band” or bit-rate independent opto-electronic regenerators with re-timing functionality [8] will alleviate this constraint, thereby “opening up” the optical network to a wider variety of client signal bit rates. Such opto-electronic regenerators will enable cascaded OTN architectures composed of a balanced combination of optical transparency and “feature-enhanced” opto-electronics supporting bit-rate and protocol independence at the optical-channel layer. Bit-rate independent opto-electronic regenerators with retiming functionality are therefore a key enabler for OTN service transparency.

**Network Maintenance**

The evolution toward optical transport networking also brings further challenges to integrated telecommunications network management. A set of requirements must be established related to fault, configuration, and performance management, including the establishment of speed, latency, and robustness requirements associated with OTN management functions and communications.

Indeed, when we examine OTN management needs, we can recognize many that are applicable to both SONET/SDH and OTN networks. However, it is essential to avoid the trap of assuming that whatever has been done for SONET/SDH is directly applicable to the optical transport network. Some of the forces that led to SONET/SDH standards were particular to that time in network evolution. For example, one of the main maintenance advantages for moving from PDH to SONET/SDH was an opportunity to significantly expand, and more importantly to truly standardize, capabilities for monitoring the validity, integrity, and quality of transport. SONET/SDH, with its digital signal format, offered a relatively painless means for these enhancements, by means of layered provision of associated maintenance overhead. Network operators saw opportunities to attempt a proactive maintenance philosophy, fueled by a computationally intensive collection of masses of data, and assign responsibilities for poor performance where a signal crosses network-operator boundaries.

Just as SONET/SDH offered an opportunity to correct some of the operating problems of the PDH network, so too will the OTN provide an opportunity to correct some of the operating problems associated with the SONET/SDH network. For example:

- A reassessment of the types and uses of performance information is in order. It has become clear that network availability has been largely unaffected by attempts at proactive maintenance strategies, and by the resultant abundance of SONET/SDH performance-monitoring information. Rather, network availability is primarily determined by components, design, and survivability decisions,
so it seems reasonable to first focus energy on quick fault localization, to speed network up repairs. Volumes of detailed performance data at every node within a subnetwork will not contribute to fault localization. On the other hand, performance data has become absolutely essential at subnetwork ingress/egress points for verifying tariffs and troubleshooting between operators. It is fortunate that performance data will be readily available at these ingress/egress points, because they are very likely to have opto-electronic processing, and thus will offer relatively easy access to both digital and analog measurements.

- Two maintenance needs were not fully realized when the first SDH/SONET standards were put in place, and have proven difficult to realize and deploy in a widespread, practical fashion. OTN maintenance offers some hope that these needs may be better satisfied. The current difficulty of knowing the physical topology of the network can be resolved by providing a trace function by means of the Optical Supervisory Channel (OSC) on each fiber segment. Additionally, requirements for tandem connection monitoring on signals that traverse multiple operator domains can be developed early in the standards process.

OTN is a very different proposition from that for SONET/SDH systems. The difficulties related to performance monitoring within optical transport networks are inherent in the parameters that need to be measured. Specifically measured optical parameters must be accurately correlated with degradations in the client-signal layers in order to indicate that the optical layers are not providing the required level of service. It is becoming clear that establishing such a relationship using practical measurement techniques remains a significant challenge [9].

Aside from details of performance monitoring and measurements, a more general and fundamental challenge remains: what operations, administration, and maintenance (OAM) information is needed at each point in the network, and how should it be carried? This information falls into two categories: information that must be associated with, and must follow, a particular optical channel connection; and information that need not necessarily follow this connection. It is the former that will provide the main challenge, because the latter can be carried in the optical supervisory channel, or through some other external means.

Our practical optical-network vision calls for a maintenance strategy aligned with an engineering approach of transparent optical subnetworks bounded by opto-electronics. As illustrated in

![Figure 7. OTN Maintenance](image-url)
Figure 7, the maintenance strategy, out of necessity, becomes a balanced combination of “opto-electronic enabled maintenance” (where opto-electronics are present) and “off-line,” shared, non-intrusive measurement and monitoring of the optically-transparent segments.

**Network Survivability**

Survivability is central to optical networking’s role as the unifying transport infrastructure. As with many other architectural aspects, optical-network survivability will bear a high-level resemblance to SONET/SDH survivability, because the network topologies and types of network elements are very similar. Within the optical layer itself, survivability mechanisms will continue to offer the fastest possible recovery from fiber cuts and other physical-media faults, as well as more efficient and flexible management of protection capacity. Recovery times will range from below 50 milliseconds to a few hundred milliseconds, depending on the particular network architecture and the type of fault. There are a variety of survivability schemes that may be considered:

For point-to-point WDM line systems involving WDM-TMs and WDM-OAs, 1+1 optical protection switching schemes similar to those for SDH/SONET are often considered. The addition of the OADM to the WDM line system will allow more advanced, optical-layer protection switching schemes, again analogous to those for SDH/SONET. Simple architectures for optical add/drop, such as 1+1 Optical SubNetwork Connection Protection (O-SNCP), are single-ended and thus do not require coordinated Automatic Protection Switching (APS) algorithms, protocols, and signaling channels. They can be applied to both linear add/drop and ring topologies.

More complex, optical-layer protection switching architectures will be capable of greater flexibility and bandwidth efficiency, especially for meshed traffic demand patterns. For ring topologies in core networks, an optical-layer version of the SDH/SONET Shared Protection Ring is a likely candidate.

The introduction of OXCs will enable optical-layer mesh-based architectures. For some applications, a mesh architecture will be lowest cost, largely due to intelligent, automated mesh restoration schemes that can be highly optimized for efficient allocation of protection capacity. Mesh-based restoration algorithms have been developed for SONET/SDH networks; however, the introduction of new optical technology and associated network elements offers opportunities for enhancements in restoration speed to support survivable optical transport network architectures. For example, distributed mesh-based restoration schemes can be employed that not only increase restoration speed, but also accommodate churn due to frequent provisioning and rearrangements, with associated algorithms that can interact constructively with a centralized capacity planning system.

While the general classes of survivable optical-network architectures are similar to those in SDH/SONET, there are some fundamental differences in functionality and applications. Survivable optical networks must provide flexible support for the requirements of a wide range of client signals, from embedded SONET/SDH rings that simply require unprotected access to WDM wavelengths to highly optimized optical-layer restoration schemes capable of differentiating among the needs of different service classes in a converged packet core. Additionally, survivable optical networks must be even more bandwidth efficient in order to support the tremendous bandwidth carried on WDM links. These gains in client networking flexibility and bandwidth efficiency also rely on a coherent multi-layer survivability strategy in which optical layer survivability mechanisms coexist gracefully with those of its client signals (for example, SONET/SDH, ATM, and IP).

Issues associated with multi-layer survivability have been cited within recent conferences (see [10]) and research consortia (see [11]). For instance, in the SONET world, consider an ATM OC-3/OC-12 based backbone network over an SONET OC-48 ring, with some of the SONET spans carried as optical channels over an OTN system. Each of these three layers – ATM, SONET, and WDM – may have survivability mechanisms; however, the absence of a cohesive multi-layer survivability approach may cause contention among the layers and result in inefficient operations and unnecessary survivability actions. More generically, there are two pitfalls to avoid in multi-layer survivability, as illustrated in Figure 8. The first involves the potential for considerable wasted bandwidth, because each layer reserves its own backup resources to use during failures. The second pitfall relates to the fact that a single physical-layer failure (such as a fiber cut) can
result in many unnecessary protection actions at the client layers. This undesirable result can greatly extend the end user’s measured outage from a single fault, potentially activating the “minimum availability” penalties of service-level agreements, as well as complicating the carrier’s maintenance tasks.

Considerable discussion is taking place within the industry regarding possible multi-layer survivability strategies. However, given the range of operator policies, services, and deployed technologies, it is clear that any proposed approaches must enable flexibility that allows them to be efficiently and cost-effectively tailored to individual operator needs. For example, an ideal approach could involve deploying only one survivability scheme per subnetwork domain per service, coupled with availability of provisionable hold-off timers for optional premium service and restoration support. As a simple case, we can consider that for most services, an optical-layer protection or restoration scheme will be desirable, because it can offer a unifying solution. Sometimes, though, it may be best to use the client layer’s survivability scheme, and disable optical-layer protection on that client’s optical channel.

In summary, optical network survivability will continue to offer the fastest possible recovery from faults, while catering to a wide diversity of client signals having varying survivability requirements.
INTEROPERABILITY

The application of any new technology, such as WDM, in the telecommunications environment requires that standards be developed to facilitate multi-vendor interworking and network interconnection. A key aspect is to fully define the information that is associated with the Optical Network Node Interface (NNI) - for example, the format of the optical supervisory channels that carry OAM information between network elements. Another key aspect involves the physical layer and requires a very precise description of the physical properties of the multi-wavelength optical signal. Not only is this an extremely difficult task to achieve for what is essentially an analog network-design problem, it is hampered by the rich diversity of options for optical transmission [7]. For example, the optimal choice of operating wavelengths for a WDM line system is dependent on a number of factors, including: type of fiber, OA technology, filter technology, span distance, and overall target reach for the system. In general, the choice of operating wavelengths is dictated by a combination of underlying technology choices coupled with the envisioned application(s).

Given the range of specifications that need to be stabilized, and the pace of technology advances, interoperability is expected to follow an evolutionary path. As a first step, multi-vendor interworking will likely be achieved by way of single-channel OTN, client-level interconnection (for example, SONET/SDH interfaces conforming to existing standards, such as ITU-T Rec. G.957). This is shown in Figure 9; again, note that the OXCs, as points of multi-vendor interoperability, are distinct from the single-vendor OADM and OLS-based subnetworks. In the near future, multi-channel OTN, client-level interconnection will occur by using standard WDM wavelengths and physical-layer parameter specifications. The above solutions imply interconnection among a network of “OTN islands” [12].

In the future, single-channel or multi-channel, OTN-level interworking will occur when full OTN-NNI specifications are available, including the specification of optical-layer overheads and the Optical Supervisory Channel. As OTN standards mature, the level of interworking will allow for optical channel-level continuity and optical networking beyond constrained transparent segments. As shown in Figure 10, OTN-level interworking will permit the independent “OTN islands” to grow, and in some cases grow together, creating larger administrative and span engineering subnetworks.

REALIZING THE OPTICAL NETWORKING VISION

The transfer of transport-layer functionality to the Optical Transport Network, concurrent with the development of a maintenance philosophy and associated OAM features, will enable evolution from single-channel optical-transmission systems to OTNs with advanced features such as optical
channel routing and wavelength conversion/interchange. It will also facilitate realizing the network operator goal of a flexible, scalable, and robust transport network, catering to an expanding variety of client signals having equally varied service requirements (flexibility, scalability, and survivability coupled with bit-rate and protocol independence). The evolutionary path to the ultimate goal of a unified transport layer will involve a number of key considerations, including the optimization of optical-layer transport functionality while maintaining client-independence. The optical layer, to remain future-proof, insofar as future-proofing is possible, should not be optimized for any particular client signal (this includes the optical-layer control plane). Just as the transport network has evolved to new signal formats, so too will today’s “networks du jour.” We need to avoid “locking-in” the optical layer to a myopic view of the future, based solely on legacy TDM and legacy (“best-effort”) data signals.

It should be emphasized that SONET/SDH will continue to be an integral part of the data/optical “convergence” networking evolution. While transport-networking responsibility will shift (dramatically, perhaps) over time, from the SONET/SDH layer to the optical layer, SONET/SDH will continue to serve the networking role for modest aggregate point-to-point bandwidth demands, such as voice trunking and many traffic types at the edges of the network. Some new telecommunications carriers will aggressively build packet-based networks from the ground up, and therefore will not have to deal with integration of legacy voice/TDM networks. On the other hand, the vast majority of carriers will find a way of integrating their current networks with emergent network infrastructures based on the optical layer.

Building the high-capacity optical transport network of the future depends on innovative solutions incorporating cutting-edge technologies coupled with sound networking principles. A Special Issue of the Bell Labs Technical Journal on Optical Networking outlines the Lucent Network Vision for leading the transition to a network of networks unified by Optical Networking, highlighting Lucent’s innovative solutions for:

- The evolution of flexible bandwidth management [13][14] and survivable network design [15] in the era of converged data/transport networking
- Architecture and protocol considerations for a converged optical data network [16][17]
- Optical Networking – the core of the next generation network infrastructure [18], from research to realization [19]
- Migrating Optical Networking toward viable metropolitan interoffice and broadband business-access transport solutions [20]
- Critical components for optical networking – optical amplifiers [21], optical add/drop technologies [22], and the future of high-capacity transport [23]
- Optical Networking solutions for enterprise and residential access applications [26][27]

**SUMMARY**

A revolution in data networking fueled by the explosive growth of the Internet is in significant measure responsible for the evolution of transport networking toward an Optical Networking infrastructure. Optical Transport Networking will leverage the transport infrastructure in the era of data/transport convergence by offering carriers unprecedented architectural flexibility – client-protocol (and bit-rate) independence, and service differentiation by separation of optical channels for different types of services (TDM, ATM, IP, optical leased lines, and so forth). With a practical vision for Optical Transport Networking, a balanced consideration of analog network engineering, service transparency, survivability, maintenance, and interoperability will render a cost-effective, survivable, and flexible broadband optical-transport infrastructure. In short, we do not have long to wait for an optical-transport network that can rise to the challenge of providing an optimized layer of high-capacity, high-reliability bandwidth management that includes multi-service support is close at hand.
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## GLOSSARY

Abbreviations Used:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>ADM</td>
<td>Add/Drop Multiplexer</td>
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<td>APS</td>
<td>Automatic Protection Switching</td>
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<td>ATM</td>
<td>Asynchronous Transfer Mode</td>
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<td>DCS</td>
<td>Digital Cross-Connect System</td>
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<td>DWDM</td>
<td>Dense Wavelength Division Multiplexing</td>
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<tr>
<td>EDFA</td>
<td>Erbium Doped Fiber Amplifier</td>
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<td>FR</td>
<td>Frame Relay</td>
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<td>IOF</td>
<td>Interoffice</td>
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<tr>
<td>IP</td>
<td>Internet Protocol</td>
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<tr>
<td>ITU</td>
<td>International Telecommunication Union</td>
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<tr>
<td>kbps</td>
<td>kilobits per second</td>
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<tr>
<td>Mbps</td>
<td>Megabits per second</td>
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<tr>
<td>NNI</td>
<td>Network Node Interface</td>
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<td>O-SNCP</td>
<td>Optical SubNetwork Connection Protection</td>
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<tr>
<td>OA</td>
<td>Optical Amplifier</td>
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<tr>
<td>OADM</td>
<td>Optical Add/Drop Multiplexer</td>
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<tr>
<td>OAM</td>
<td>Operations, Administration, and Maintenance</td>
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<tr>
<td>OCh</td>
<td>Optical Channel</td>
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<tr>
<td>OLS</td>
<td>Optical Line System</td>
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<td>OSC</td>
<td>Optical Supervisory Channel</td>
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<td>OTN</td>
<td>Optical Transport Network</td>
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<tr>
<td>OXC</td>
<td>Optical Cross Connect</td>
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<td>PDH</td>
<td>Plesiochronous Digital Hierarchy</td>
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<tr>
<td>PSTN</td>
<td>Public Switched Telephone Network</td>
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<tr>
<td>SDH</td>
<td>Synchronous Digital Hierarchy</td>
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<tr>
<td>SNCP</td>
<td>SubNetwork Connection Protection</td>
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<tr>
<td>SONET</td>
<td>Synchronous Optical Network</td>
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<td>TDM</td>
<td>Time-Division Multiplexing</td>
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<tr>
<td>TM</td>
<td>Terminal Multiplexer</td>
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<tr>
<td>Tbps</td>
<td>Terabits per second</td>
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<tr>
<td>VPN</td>
<td>Virtual Private Network</td>
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<td>WDM</td>
<td>Wavelength Division Multiplexing</td>
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