Ethernet Passive Optical Networks

Definition

Ethernet passive optical networks (EPON) are an emerging access network technology that provides a low-cost method of deploying optical access lines between a carrier's central office (CO) and a customer site. EPONs build on the International Telecommunications Union (ITU) standard G.983 for asynchronous transfer mode PONs (APON) and seek to bring to life the dream of a full-services access network (FSAN) that delivers converged data, video, and voice over a single optical access system.

Overview

The communications industry is on the cusp of a revolution that will transform the landscape. This revolution is characterized by three fundamental drivers. First, deregulation has opened the local loop to competition, launching a whole new class of carriers that are spending billions to build out their networks and develop innovative new services. Second, the rapid decline in the cost of fiber optics and Ethernet equipment is beginning to make them an attractive option in the access network. Third, the Internet has spawned genuine demand for broadband services, leading to unprecedented growth in Internet protocol (IP) data traffic and putting pressure on carriers to upgrade their networks.

These drivers are, in turn, promoting two new key market trends. First, deployment of fiber optics is extending from the backbone to the wide-area network (WAN) and the metropolitan-area network (MAN) and will soon penetrate into the local loop. Second, Ethernet is spreading from the local-area network (LAN) to the MAN and the WAN as the uncontested standard.

The convergence of these factors is leading to a fundamental paradigm shift in the communications industry, a shift that will ultimately lead to widespread adoption of a new optical IP Ethernet architecture that combines the best of fiber optics and Ethernet technologies. This architecture is poised to become the dominant means of delivering bundled data, video, and voice services over a single platform.

This tutorial discusses the economics, technological underpinnings, features and benefits, and history of EPONs.

Topics

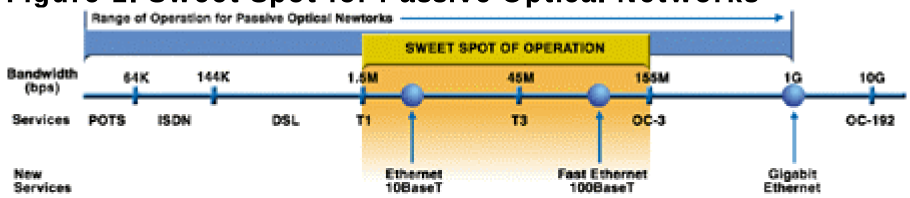
1. Evolution of Passive Optical Networks

Passive optical networks (PONs) address the last mile of the communications infrastructure between the service provider's CO, head end, or point of presence (POP) and business or residential customer locations. Also known as the access network or local loop, the last mile consists predominantly, in residential areas, of copper telephone wires or coaxial cable television (CATV) cables. In metropolitan areas, where there is a high concentration of business customers, the access network often includes high-capacity synchronous optical network (SONET) rings, optical T3 lines, and copper-based T1s.

Typically, only large enterprises can afford to pay the $3,200 – $4,300 per month it costs to lease a T3 (45 Mbps) or optical carrier (OC)–3 (155 Mbps) SONET connection. T1s at $375 per month are an option for some medium-size enterprises, but most small and medium-size enterprises and residential customers are left with few options beyond plain old telephone service (POTS) and dial-up Internet access. Where available, digital subscriber line (DSL) and cable modems offer a more affordable interim solution for data, but they are difficult and time-consuming to provision. In addition, bandwidth is limited by distance and by the quality of existing wiring; and voice services have yet to be widely implemented over these technologies.

Even as the access network remains at a relative standstill, bandwidth is increasing dramatically on longhaul networks through the use of wavelength division multiplexing (WDM) and other new technologies. Recently, WDM technology has even begun to penetrate metropolitan-area networks (MAN), boosting their capacity dramatically. At the same time, enterprise local-area networks (LAN) have moved from 10 Mbps to 100 Mbps, and soon many LANs will be upgraded to gigabit Ethernet speeds. The result is a growing gulf between the capacity of metro networks on one side and end-user needs on the other, with the last-mile bottleneck in between.

Figure 1. Sweet Spot for Passive Optical Networks



PONs aim to break the last-mile bandwidth bottleneck by targeting the sweet spot between T1s and OC–3s that other access network technologies do not adequately address.

The two primary types of PON technology are asynchronous transfer mode PONs (APONs) and Ethernet PONs (EPONs).

APONs

APONs were developed in the mid 1990s through the work of the full-service access network (FSAN) initiative. FSAN was a group of 20 large carriers that worked with their strategic equipment suppliers to agree upon a common broadband access system for the provisioning of both broadband and narrowband services. British Telecom organized the FSAN Coalition in 1995 to develop standards for designing the cheapest, fastest way to extend emerging high-speed services, such as Internet protocol (IP) data, video, and 10/100 Ethernet, over fiber to residential and business customers worldwide.

At that time the two logical choices for protocol and physical plant were ATM and PON: ATM because it was thought to be suited for multiple protocols, PON because it is the most economical broadband optical solution. The APON format used by FSAN was accepted as an International Telecommunications Union (ITU) standard (ITU–T Rec. G.983). The ITU standard focused primarily on residential applications and in its initial version did not include provisions for delivering video services over the PON. Subsequently, a number of start-up vendors introduced APON–compliant systems that focused exclusively on the business market.

EPONs

The development of EPONs has been spearheaded by one or two visionary start-ups that feel that the APON standard is an inappropriate solution for the local loop because of its lack of video capabilities, its insufficient bandwidth, its complexity, and its expense. Also, as the move to fast Ethernet, gigabit Ethernet, and now 10-gigabit Ethernet picks up steam, these start-ups believe that EPONs will eliminate the need for conversion in the wide-area network (WAN)/LAN connection between ATM and IP protocols.

EPON vendors are focusing initially on developing fiber-to-the-business (FTTB) and fiber-to-the-curb (FTTC) solutions, with the long-term objective of realizing a full-service fiber-to-the-home (FTTH) solution for delivering data, video, and voice over a single platform. While EPONs offer higher bandwidth, lower costs, and broader service capabilities than APON, the architecture is broadly similar and adheres to many G.983 recommendations.

In November 2000, a group of Ethernet vendors kicked off their own standardization effort, under the auspices of the Institute of Electrical and Electronics Engineers (IEEE), through the formation of the Ethernet in the First Mile (EFM) study group. The new study group aims to develop a standard that will apply the proven and widely used Ethernet networking protocol to the access market. Sixty-nine companies, including 3Com, Alloptic, Aura Networks, CDT/Mohawk, Cisco Systems, DomiNet Systems, Intel, MCI WorldCom, and World Wide Packets, have indicated they will participate in the group.

2. Economic Case for Ethernet PONs

The economic case for EPONs is simple: fiber is the most effective medium for transporting data, video, and voice traffic, and it offers virtually unlimited bandwidth. But the cost of running fiber “point-to-point” from every customer location all the way to the CO, installing active electronics at both ends of each fiber, and managing all of the fiber connections at the CO is prohibitive. EPONs address the shortcomings of point-to-point fiber solutions by using a point-to-multipoint topology instead of point-to-point in the outside plant; by eliminating active electronic components, such as regenerators, amplifiers, and lasers, from the outside plant; and by reducing the number of lasers needed at the CO.

Table 1. Comparison of Point-to-Point Fiber Access and EPONs

Point-to-Point Fiber Access	EPON
Point-to-Point Architecture	Point-to-Multipoint Architecture
Active electronic components are required at the end of each fiber and in the outside plant.	Eliminates active electronic components, such as regenerators and amplifiers, from the outside plant and replaces them with less-expensive passive optical couplers that are simpler, easier to maintain, and longer lived than active components
Each subscriber requires a separate fiber port in the CO.	Conserves fiber and port space in the CO by passively coupling traffic from up to 64 optical network units (ONU) onto a single fiber that runs from a neighborhood demarcation point back to the service provider's CO, head end, or POP
Expensive active electronic components are dedicated to each subscriber	Cost of expensive active electronic components and lasers in the optical line terminal (OLT) is shared over many subscribers

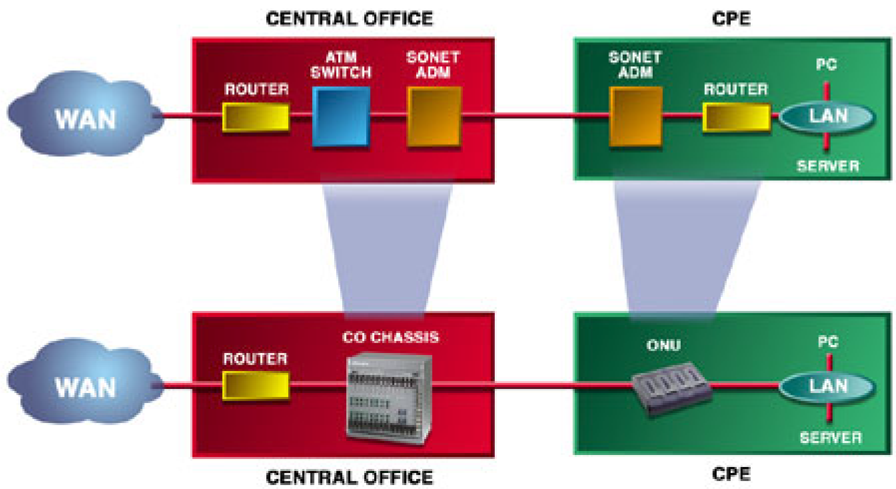
Unlike point-to-point fiber-optic technology, which is optimized for metro and longhaul applications, EPONs are tailor-made to address the unique demands of the access network. Because they are simpler, more efficient, and less expensive than alternative access solutions, EPONs finally make it cost-effective for service providers to extend fiber into the last mile and to reap all the rewards of a very efficient, highly scalable, low-maintenance, end-to-end fiber-optic network.

The key advantage of an EPON is that it allows carriers to eliminate complex and expensive asynchronous transfer mode (ATM) and SONET elements and to simplify their networks dramatically. Traditional telecom networks use a complex, multilayered architecture, which overlays IP over ATM, SONET, and WDM. This architecture requires a router network to carry IP traffic, ATM switches to create virtual circuits, add/drop multiplexers (ADM) and digital cross-connects (DCS) to manage SONET rings, and point-to-point DWDM optical links.

There are a number of limitations inherent to this architecture: (1) it is fiendishly difficult to provision because each network element (NE) in an ATM path must be provisioned for each service; (2) it is optimized for time division multiplex (TDM) voice—not data—so its fixed bandwidth channels have difficulty handling bursty data traffic; (3) it requires inefficient and expensive optical-to-electrical-to-optical (O–E–O) conversion at each network node; (4) it requires installation of all nodes up front (because each node is a regenerator); and (5) it does not scale well because of its connection-oriented virtual circuits.

In the example of a streamlined EPON architecture in *Figure 2*, an ONU replaces the SONET ADM and router at the customer premises, and an OLT replaces the SONET ADM and ATM switch at the CO.

Figure 2. Streamlined EPON Architecture

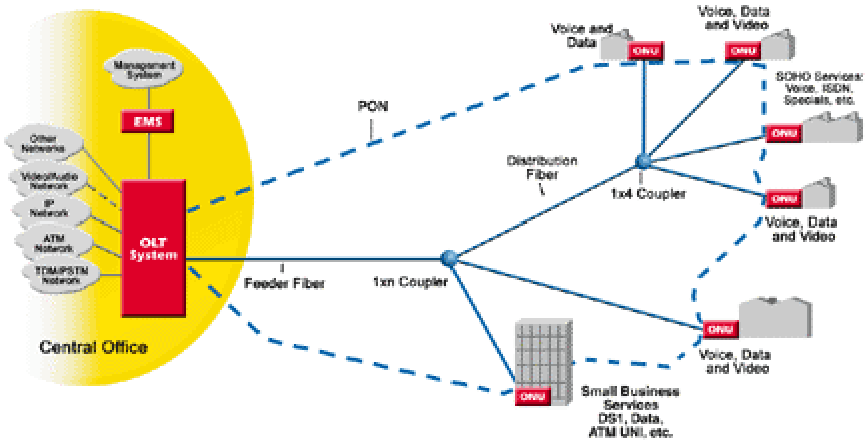


This architecture offers carriers a number of benefits. First, it lowers up front capital equipment and ongoing operational costs relative to SONET and ATM. Second, an EPON is easier to deploy than SONET/ATM because it requires less complex hardware and no outside plant electronics, which reduces the need for experienced technicians. Third, it facilitates flexible provisioning and rapid service reconfiguration. Fourth, it offers multilayered security, such as virtual LAN (VLAN) closed user groups and support for virtual private network (VPN), IP security (IPSec), and tunneling. Finally, carriers can boost their revenues by exploiting the broad range and flexibility of services offerings available over an EPON architecture. This includes delivering bandwidth in scalable increments from 1 to 100 Mbps up to 1 Gbps and value-added services, such as managed firewalls, voice traffic support, VPNs, and Internet access.

3. Passive Optical Network Architecture

The passive elements of an EPON are located in the optical distribution network (also known as the outside plant) and include single-mode fiber-optic cable, passive optical splitters/couplers, connectors, and splices. Active NEs, such as the OLT and multiple ONUs, are located at the end points of the PON. Optical signals traveling across the PON are either split onto multiple fibers or combined onto a single fiber by optical splitters/couplers, depending on whether the light is traveling up or down the PON. The PON is typically deployed in a single-fiber, point-to-multipoint, tree-and-branch configuration for residential applications. The PON may also be deployed in a protected ring architecture for business applications or in a bus architecture for campus environments and multiple-tenant units (MTU).

Figure 3. Passive and Active NEs of a PON



4. Active Network Elements

EPON vendors focus on developing the “active” electronic components—such as the CO chassis and ONUs—that are located at both ends of the PON. The CO chassis is located at the service provider’s CO, head end, or POP and houses OLTs, network interface modules (NIM), and the switch card module (SCM). The PON connects an OLT card to 64 ONUs, each located at a home, business, or MTU. The ONU provides customer interfaces for data, video, and voice services, as well network interfaces for transmitting traffic back to the OLT.

CO Chassis

The CO chassis provides the interface between the EPON system and the service provider’s core data, video, and telephony networks. The chassis also links to the service provider’s core operations networks through an element management system (EMS). WAN interfaces on the CO chassis will typically interface with the following types of equipment:

- DCSs, which transport nonswitched and non–locally switched TDM traffic to the telephony network. Common DCS interfaces include digital signal (DS)–1, DS–3, synchronous transport signal (STS)–1, and OC–3.

- Voice gateways, which transport locally switched TDM/voice traffic to the public-switched telephone network (PSTN)
- IP routers or ATM edge switches, which direct data traffic to the core data network
- Video network devices, which transport video traffic to the core video network
- Key functions and features of the CO chassis include the following:
- Multiservice interface to the core WAN
- Gigabit Ethernet interface to the PON
- Layer-2 and -3 switching and routing
- Quality of service (QoS) issues and service-level agreements (SLA)
- Traffic aggregation
- Houses OLTs and SCM

Optical Network Unit

The ONU provides the interface between the customer's data, video, and telephony networks and the PON. The primary function of the ONU is to receive traffic in an optical format and convert it to the customer's desired format (Ethernet, IP multicast, POTS, T1, etc.). A unique feature of EPONs is that, in addition to terminating and converting the optical signal, the ONUs provide Layer-2 and -3 switching functionality, which allows internal routing of enterprise traffic at the ONU. EPONs are also well suited to delivering video services in either analog CATV format, using a third wavelength, or IP video.

Because an ONU is located at every customer location in FTTB and FTTH applications and the costs are not shared over multiple subscribers, the design and cost of the ONU is a key factor in the acceptance and deployment of EPON systems. Typically, the ONUs account for more than 70 percent of the system cost in FTTB deployments, and in FTTH deployments they account for approximately 80 percent.

Key features and functions of the ONU include the following:

- Customer interfaces for POTS, T1, DS–3, 10/100BASE-T, IP multicast, and dedicated wavelength services

- Layer-2 and -3 switching and routing capabilities
- Provisioning of data in 64 kbps increments up to 1 Gbps
- Low start-up costs and plug-and-play expansion
- Standard Ethernet interfaces eliminate the need for additional DSL or cable modems

EMS

The EMS manages the different elements of the PON and provides the interface into the service provider's core operations network. Its management responsibilities include the full range of fault, configuration, accounting, performance, and security (FCAPS) functions.

Key features and functions of the EMS include the following:

- Full FCAPS functionality via a modern graphical user interface (GUI)
- Capable of managing dozens of fully equipped PON systems
- Supports hundreds of simultaneous GUI users
- Standard interfaces, such as common object request broker architecture (CORBA), to core operations networks

5. How Ethernet PONs Work

The key difference between EPONs and APONs is that in EPONs, data is transmitted in variable-length packets of up to 1,518 bytes according to the IEEE 802.3 protocol for Ethernet, whereas in APONs, data is transmitted in fixed-length 53-byte cells (with 48-byte payload and five-byte overhead), as specified by the ATM protocol. This format means it is difficult and inefficient for APONs to carry traffic formatted according to the IP. The IP calls for data to be segmented into variable-length packets of up to 65,535 bytes. For an APON to carry IP traffic, the packets must be broken into 48-byte segments with a 5-byte header attached to each one. This process is time consuming and complicated and adds additional cost to the OLT and ONUs. Moreover, 5 bytes of bandwidth are wasted for every 48-byte segment, creating an onerous overhead that is commonly referred to as the "ATM cell tax." By contrast, Ethernet was tailor-made for carrying IP traffic and dramatically reduces the overhead relative to ATM.

Managing Upstream / Downstream Traffic in an EPON

In an EPON, the process of transmitting data downstream from the OLT to multiple ONUs is fundamentally different from transmitting data upstream from multiple ONUs to the OLT. The different techniques used to accomplish downstream and upstream transmission in an EPON are illustrated in *Figures 4* and *5*.

In *Figure 4*, data is broadcast downstream from the OLT to multiple ONUs in variable-length packets of up to 1,518 bytes, according to the IEEE 802.3 protocol. Each packet carries a header that uniquely identifies it as data intended for ONU–1, ONU–2, or ONU–3. In addition, some packets may be intended for all of the ONUs (broadcast packets) or a particular group of ONUs (multicast packets). At the splitter, the traffic is divided into three separate signals, each carrying all of the ONU–specific packets. When the data reaches the ONU, it accepts the packets that are intended for it and discards the packets that are intended for other ONUs. For example, in *Figure 4*, ONU–1 receives packets 1, 2, and 3; however, it delivers only packet 1 to end user 1.

Figure 4. Downstream Traffic Flow in an EPON

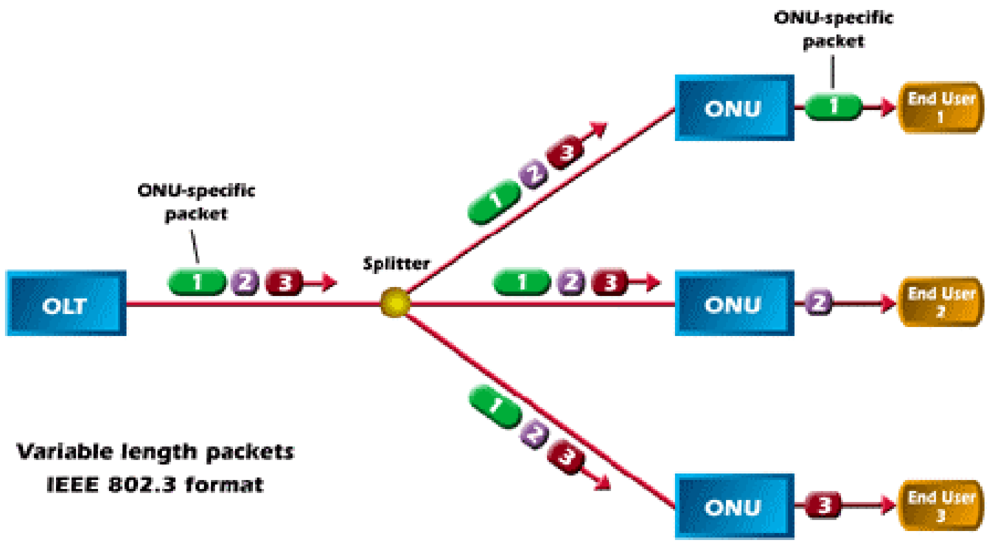
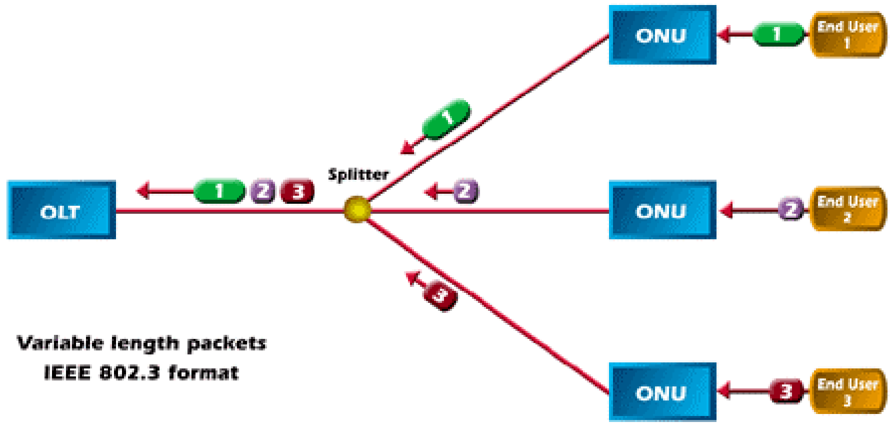


Figure 5 shows how upstream traffic is managed utilizing TDM technology, in which transmission time slots are dedicated to the ONUs. The time slots are synchronized so that upstream packets from the ONUs do not interfere with each other once the data is coupled onto the common fiber. For example, ONU–1 transmits packet 1 in the first time slot, ONU–2 transmits packet 2 in a second non-overlapping time slot, and ONU–3 transmits packet 3 in a third non-overlapping time slot.

Figure 5. Upstream Traffic Flow in an EPON



EPON Frame Formats

Figure 6 depicts an example of downstream traffic that is transmitted from the OLT to the ONUs in variable-length packets. The downstream traffic is segmented into fixed-interval frames, each of which carries multiple variable-length packets. Clocking information, in the form of a synchronization marker, is included at the beginning of each frame. The synchronization marker is a one-byte code that is transmitted every 2 ms to synchronize the ONUs with the OLT.

Each variable-length packet is addressed to a specific ONU as indicated by the numbers, 1 through *N*. The packets are formatted according to the IEEE 802.3 standard and are transmitted downstream at 1 Gbps. The expanded view of one variable-length packet shows the header, the variable-length payload, and the error-detection field.

Figure 6. Downstream Frame Format in an EPON

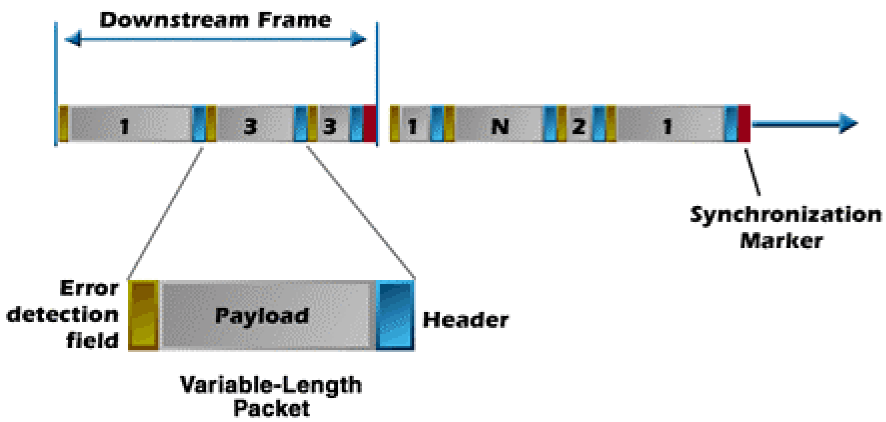


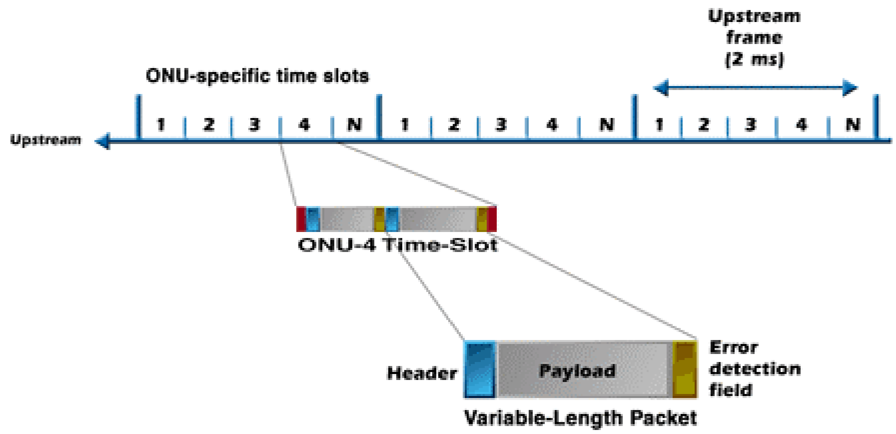
Figure 7 depicts an example of upstream traffic that is TDMed onto a common optical fiber to avoid collisions between the upstream traffic from each ONU. The

upstream traffic is segmented into frames, and each frame is further segmented into ONU–specific time slots. The upstream frames are formed by a continuous transmission interval of 2 ms. A frame header identifies the start of each upstream frame.

The ONU–specific time slots are transmission intervals within each upstream frame that are dedicated to the transmission of variable-length packets from specific ONUs. Each ONU has a dedicated time slot within each upstream frame. For example, in *Figure 7*, each upstream frame is divided into *N* time slots, with each time slot corresponding to its respective ONU, 1 through *N*.

The TDM controller for each ONU, in conjunction with timing information from the OLT, controls the upstream transmission timing of the variable-length packets within the dedicated time slots. *Figure 8* shows an expanded view of the ONU–specific time slot (dedicated to ONU–4) that includes two variable-length packets and some time-slot overhead. The time-slot overhead includes a guard band, timing indicators, and signal power indicators. When there is no traffic to transmit from the ONU, a time slot may be filled with an idle signal.

Figure 7. Upstream Frame Format in an EPON



6. Optical System Design

EPONs can be implemented using either a two-wavelength or a three-wavelength design. The two-wavelength design is suitable for delivering data, voice, and IP–switched digital video (SDV). A three-wavelength design is required to provide radio frequency (RF) video services (CATV) or dense wavelength division multiplexing (DWDM).

Figure 8 shows the optical layout for a two-wavelength EPON. In this architecture, the 1510 nm wavelength carries data, video, and voice downstream, while a 1310 nm wavelength is used to carry video-on-demand (VOD)/channel change requests, as well as data and voice, upstream. Using a 1.25 Gbps bidirectional PON, the optical loss with this architecture gives the PON a reach of 20 km over 32 splits.

Figure 8. Optical Design for Two-Wavelength EPON

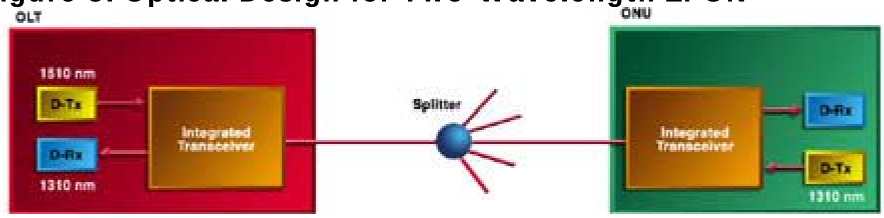
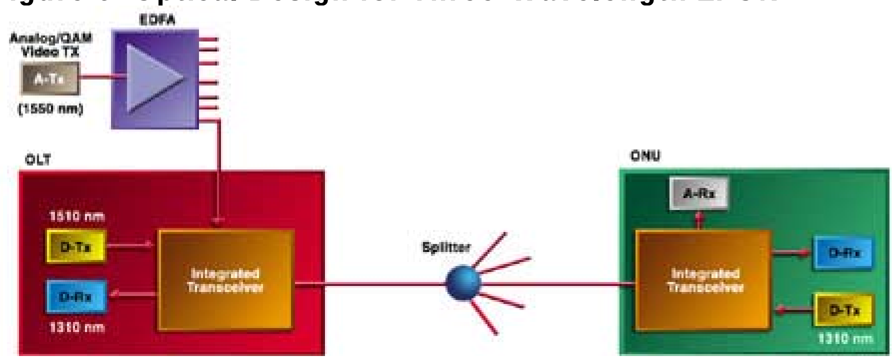


Figure 9 shows the optical layout for a three-wavelength EPON. In this architecture, 1510 nm and 1310 nm wavelengths are used in the downstream and the upstream directions respectively, while the 1550 nm wavelength is reserved for downstream video. The video is encoded as Moving Pictures Experts Group–Layer 2 (MPEG2) and is carried over quadrature amplitude modulation (QAM) carriers. Using this setup, the PON has an effective range of 18 km over 32 splits.

Figure 9. Optical Design for Three-Wavelength EPON



The three-wavelength design can also be used to provide a DWDM overlay to an EPON. This solution uses a single fiber with 1510 nm downstream and 1310 nm upstream. The 1550 nm window (1530–1565 nm) is left unused, and the transceivers are designed to allow DWDM channels to ride atop the PON transparently. The PON can then be deployed with no DWDM components, while allowing future DWDM upgrades to provide wavelength services, analog video, increased bandwidth, etc. In this context, EPONs offer an economical setup cost, which scales effectively to meet future demand.

7. Quality of Service

EPONs offer many cost and performance advantages that enable service providers to deliver revenue-generating services over a highly economical platform. However, a key technical challenge for EPON vendors lies in enhancing Ethernet’s capabilities to ensure that real-time voice and IP video services can be delivered over a single platform with the same QoS and ease of management as ATM or SONET.

EPON vendors are attacking this problem from several angles. The first is to implement methods, such as differentiated services (DiffServ) and 802.1p, which prioritize traffic for different levels of service. One such technique, TOS Field, provides eight layers of prioritization to make sure that the packets go through in order of importance. Another technique, called bandwidth reserve, provides an open highway with guaranteed latency for POTS traffic so that it does not have to contend with data.

To illustrate some of the different approaches to emulating ATM/SONET service capabilities in an EPON, *Table 2* highlights four key objectives that ATM and SONET have been most effective at providing: (1) the quality and reliability required for real-time services; (2) statistical multiplexing to manage network resources effectively; (3) multiservice delivery to allocate bandwidth fairly among users; (4) tools to provision, manage, and operate networks and services; and (5) full system redundancy and restoration.

In every case, EPONs have been designed to deliver comparable services and objectives using Ethernet and IP technology. Sometimes this has required the development of innovative techniques, which are not adequately reflected in literal line-by-line adherence to ATM or SONET standards and features.

Table 2. Comparison of ATM, SONET, and EPON Service Objectives and Solutions

Objective	ATM/SONET Solution	Ethernet PON Solution
Real-time services	ATM service architecture and connection-oriented design ensure the reliability and quality needed for real-time service.	A routing/switching engine that offers native IP/Ethernet classification with advanced admission control, bandwidth guarantees, traffic shaping, and network resource management that extends significantly beyond the Ethernet solutions found in traditional enterprise LANs
Statistical multiplexing	Traffic shaping and network resource management allocates bandwidth fairly between users of non–real-time services Dynamic bandwidth allocation implementation needed.	Traffic-management functionality across the internal architecture and the external interface with the MAN EMS provides coherent policy based traffic management across OLTs and ONUs. IP traffic flow is inherently bandwidth conserving (statistical multiplexing).
Multiservice delivery	These characteristics work together to ensure that fairness is maintained among different services coexisting on a	Service priorities and SLAs assure that network resources are always available for a customer-specific service. Gives service provider control of "walled-garden"

	common network.	services, such as CATV and interactive IP video.
Management capabilities	A systematic provisioning framework and advanced management functionality enhance the operational tools available to manage the network.	Integrating EMS with service providers' OSSs emulates the benefits of connection-oriented networks and facilitates end-to-end provisioning, deployment, and management of IP services.
Protection	Bidirectional line-switched ring (BLSR) and unidirectional path-switched ring (UPSR) provide full system redundancy and restoration.	Counter-rotating ring architecture provides protection switching in sub 50 ms intervals.

These techniques allow EPONs to deliver the same reliability, security, and QoS as more expensive SONET and ATM solutions.

- Guaranteed QoS using TOS Field and DiffServ
- Full system redundancy providing high availability and reliability
- Diverse ring architecture with full redundancy and path protection
- Multilayered security, such as VLAN closed user groups and support for VPN, IPSec, and tunneling

8. Applications

EPONs address a variety of applications for incumbent local-exchange carriers (ILEC), cable multiple-system operators (MSO), competitive local-exchange carriers (CLEC), building local-exchange carriers (BLEC), overbuilders (OVB), utilities, and emerging start-up service providers. These applications can be broadly classified into three categories:

- Cost reduction: reducing the cost of installing, managing, and delivering existing services
- New revenue opportunities: boosting revenue-earning opportunities through the creation of new services
- Competitive advantage: increasing carrier competitiveness by enabling more rapid responsiveness to new business models or opportunities

Cost-Reduction Applications

EPONs offer service providers unparalleled opportunities to reduce the cost of installing, managing, and delivering existing service offerings. For example, EPONs do the following:

- Replace active electronic components with less expensive passive optical couplers that are simpler, easier to maintain, and longer lived
- Conserve fiber and port space in the CO
- Share the cost of expensive active electronic components and lasers over many subscribers
- Deliver more services per fiber and slash the cost per megabit
- Promise long-term cost-reduction opportunities based on the high volume and steep price/performance curve of Ethernet components
- Save the cost of truck rolls because bandwidth allocation can be done remotely
- Free network planners from trying to forecast the customer's future bandwidth requirement because the system can scale up easily

For service providers the result is lower capital costs, reduced capital expenditures, and higher margins.

Case Study: T1 Replacement

ILECs realize that T1 services are their "bread and butter" in the business market. However, T1 lines can be expensive to maintain and provision, particularly where distance limitations require the use of repeaters. Today, most T1s are delivered over copper wiring, but service providers have already recognized that fiber is more cost-effective when demand at a business location exceeds four T1 lines.

EPONs provide the perfect solution for service providers that want to consolidate multiple T1s on a single cost-effective fiber. By utilizing a PON, service providers eliminate the need for outside plant electronics, such as repeaters. As a result, the expense required to maintain T1 circuits can be reduced dramatically. In many cases, savings of up to 40 percent on maintenance can be achieved by replacing repeatered T1 circuits with fiber-based T1s.

New Revenue Opportunities

New revenue opportunities are a critical component of any service provider's business plan. Infrastructure upgrades must yield a short-term return on investment and enable the network to be positioned for the future. EPON platforms do exactly that by delivering the highest bandwidth capacity available today, from a single fiber, with no active electronics in the outside plant. The immediate benefit to the service provider is a low initial investment per subscriber and an extremely low cost per megabit. In the longer term, by leveraging an EPON platform, carriers are positioned to meet the escalating demand for bandwidth as well as the widely anticipated migration from TDM to Ethernet solutions.

Case Study: Fast Ethernet and Gigabit Ethernet

Increasing growth rates for Ethernet services have confirmed that the telecommunications industry is moving aggressively from a TDM orientation to a focus on Ethernet solutions. Fast Ethernet (10/100BT) is expected to grow at a rate of 25.2 percent compound annual growth rate (CAGR) 1999–2004 (IDC, June 2000). Gigabit Ethernet is experiencing an extremely rapid growth of 128.9 percent CAGR 1999–2004 (IDC, June 2000). It is imperative that incumbent carriers, MSOs, and new service providers embrace these revenue streams. The challenge for the ILEC is how to implement these new technologies aggressively without marginalizing existing products. For new carriers, it is critical to implement these technologies with a minimum of capital expenditure. MSOs are concerned about how best to leverage their existing infrastructure while introducing new services.

EPONs provide the most cost-effective means for ILECs, CLECs, and MSOs to roll out new, higher-margin fast Ethernet and gigabit Ethernet services to customers. Data rates are scalable from 1 Mbps to 1 Gbps, and new equipment can be installed incrementally as service needs grow, which conserves valuable capital resources. In an analysis of the MSO market, an FTTB application delivering 10/100BASE-T and T1 circuits yielded a one-month payback (assuming a ratio of 70 percent 10/100BASE-T to 30 percent T1, excluding fiber cost).

Competitive Advantage

Since the advent of the Telecommunications Act of 1996, competition has been on the increase. However, the current state of competition has been impacted by the capital crisis within the service-provider community. CLECs today are increasingly focused on market niches that provide fast growth and short-term return on investment.

Incumbent carriers must keep focused on core competencies while defending market-share, and, at the same time, they must look for high-growth new product opportunities. One of the most competitive niches being focused on is the Ethernet space. Long embraced as the de facto standard for LANs, Ethernet is used in more than 90 percent of today's computers. From an end-user perspective, Ethernet is less complex and less costly to manage. Service providers, both incumbent and new entrants, are providing these services as both an entry and defensive strategy. From the incumbent perspective, new entrants that offer low-cost Ethernet connectivity will take market-share from legacy products. As a defensive strategy, incumbents must meet the market in a cost-effective, aggressive manner. EPON systems are an extremely cost-effective way to maintain a competitive edge.

Case Study: Enabling New Service-Provider Business Models

New or next-generation service providers know that a key strategy in today's competitive environment is to keep current cost at a minimum, with an access platform that provides a launch pad for the future. EPON solutions fit the bill. EPONs can be used for both legacy and next-generation service, and they can be provisioned on a pay-as-you-go-basis. This allows the most widespread deployment with the least up-front investment.

For example, a new competitive service provider could start by deploying a CO chassis with a single OLT card feeding one PON and five ONUs. This simple, inexpensive architecture enables the delivery of eight DS–1, three DS–3, 46 100/10BASE-T, one gigabit Ethernet (DWDM), and two OC–12 (DWDM) circuits, while leaving plenty of room in the system for expansion. For a new service provider, this provides the benefit of low initial start-up costs, a wide array of new revenue-generating services, and the ability to expand network capacity incrementally as demand warrants.

9. Benefits of Ethernet PONs

EPONs are simpler, more efficient, and less expensive than alternate multiservice access solutions. Key advantages of EPONs include the following:

- Higher bandwidth: up to 1.25 Gbps symmetric Ethernet bandwidth
- Lower costs: lower up-front capital equipment and ongoing operational costs
- More revenue: broad range of flexible service offerings means higher revenues

Higher Bandwidth

EPONs offer the highest bandwidth to customers of any PON system today. Downstream traffic rates of 1 Gbps in native IP have already been achieved, and return traffic from up to 64 ONUs can travel in excess of 800 Mbps.

The enormous bandwidth available on EPONs provides a number of benefits:

- More subscribers per PON
- More bandwidth per subscriber
- Higher split counts
- Video capabilities
- Better QoS

Lower Costs

EPON systems are riding the steep price/performance curve of optical and Ethernet components. As a result, EPONs offer the features and functionality of fiber-optic equipment at price points that are comparable to DSL and copper T1s. Further cost reductions are achieved by the simpler architecture, more efficient operations, and lower maintenance needs of an optical IP Ethernet network.

EPONs deliver the following cost reduction opportunities:

- Eliminate complex and expensive ATM and SONET elements and dramatically simplify network architecture
- Long-lived passive optical components reduce outside plant maintenance
- Standard Ethernet interfaces eliminate the need for additional DSL or cable modems
- No electronics in outside plant reduces need for costly powering and right-of-way space

More Revenue

EPONs can support a complete bundle of data, video, and voice services, which allows carriers to boost revenues by exploiting the broad range and flexibility of service offerings available. In addition to POTS, T1, 10/100BASE-T, and DS–3, EPONs support advanced features, such as Layer-2 and -3 switching, routing, voice over IP (VoIP), IP multicast, VPN 802.1Q, bandwidth shaping, and billing. EPONs also make it easy for carriers to deploy, provision, and manage services. This is primarily because of the simplicity of EPONs, which leverage widely accepted, manageable, and flexible Ethernet technologies.

Revenue opportunities from EPONs include:

- Support for legacy TDM, ATM, and SONET services
- Delivery of new gigabit Ethernet, fast Ethernet, IP multicast, and dedicated wavelength services
- Provisioning of bandwidth in scalable 64 kbps increments up to 1 Gbps
- Tailoring of services to customer needs with guaranteed SLAs
- Quick response to customer needs with flexible provisioning and rapid service reconfiguration

Table 3. Summary of EPON Features and Benefits

Features	**Benefits**
ONUs provide internal IP address translation, which reduces the number of IP addresses and interfaces with PC and data equipment over widely used Ethernet interfaces.	Customer configuration changes can be made without coordination of ATM addressing schemes that are less flexible.
ONU offers similar features to routers, switches and hubs at no additional cost.	Consolidates functions into one box, simplifies network, and reduces costs
Software-activated VLANs	Allows service providers to generate new service revenues
Implement firewalls at the ONU without need for separate PC	Allows service providers to generate new service revenues
Full system redundancy to the ONU provides high availability and reliability (five 9s).	Allows service providers to guarantee service levels and avoid costly outages
Self-healing network architecture with complete back-up databases	Allows rapid restoration of services with minimal effort in the event of failure
Automatic equipment self-identification	Facilitates services restoration upon equipment recovery or card replacement
Remote management and software upgrades	Simplifies network management,

	reduces staff time, and cuts costs
Status of voice, data, and video services for a customer or group of customers can be viewed simultaneously.	Facilitates better customer service and reduces cost of handling customer inquiries
ONUs have standard Ethernet customer interface.	Eliminates need for separate DSL and/or cable modems at customer premises and lowers cost

10. Ethernet in the First Mile Initiative

EPON vendors are actively engaged in a new study group that will investigate the subject of EFM. Established under the auspices of the IEEE, the new study group aims to develop a standard that will apply the proven and widely used Ethernet networking protocol to the access market.

The EFM study group was formed within the IEEE 802.3 carrier sense multiple access with collision detection (CSMA/CD) Working Group in November 2000. Sixty-nine companies, including 3Com, Alloptic, Aura Networks, CDT/Mohawk, Cisco Systems, DomiNet Systems, Intel, MCI WorldCom, and World Wide Packets, have indicated they will participate in the group.

In addition to the IEEE study group, EPON vendors are planning to participate in other standards efforts conducted within organizations, such as the Internet Engineering Task Force (IETF), ITU–Telecommunications Standardization Sector (ITU–T), and the Standards Committee T1. There is even the possibility of a liaison with FSAN on this effort. The FSAN document does not preclude non–ATM protocols, and the FSAN document is broad in scope (covering many last-mile issues). Much of G.983 remains valid, and it could be that the IEEE 802.3 EFM group will focus on developing the MAC protocols for EPON, referencing FSAN for everything else. This is the quickest path to an EPON standard, and several big names, including Cisco Systems and Nortel Networks, are backing EPON over APON.

11. The Future of Ethernet PONs

EPONs are in the early phases of commercial development with initial trial deployments anticipated during 2001. Although APONs have a slight head start in the marketplace, current industry trends—including the rapid growth of data traffic and the increasing importance of fast Ethernet and gigabit Ethernet services—favor Ethernet PONs. Standardization efforts are already underway based on the establishment of the EFM study group, and momentum is building for an upgrade to the FSAN–initiated APON standard.

The stage is set for a paradigm-shift in the communications industry that could well result in a completely new “equipment deployment cycle,” firmly grounded in the wide-based adoption of fiber optics and Ethernet technologies. This optical IP Ethernet architecture promises to become the dominant means of delivering bundled voice, data, and video services over a single network. In addition, this architecture is an enabler for a new generation of cooperative and strategic partnerships, which will bring together content providers, service providers, network operators, and equipment manufacturers to deliver a bundled entertainment and communications package unrivaled by any other past offering.

Self-Test

1. Also known as the access network or local loop, the _________________ consists predominantly, in residential areas, of copper telephone wires or coaxial cable television (CATV) cables.

    a. customer premises

    b. hardware

    c. last mile

    d. network

2. ______________ address the shortcomings of point-to-point fiber solutions by using a point-to-multipoint topology instead of point-to-point in the outside plant; by eliminating active electronic components, such as regenerators, amplifiers, and lasers, from the outside plant; and by reducing the number of lasers needed at the CO.

    a. EPONs

    b. Engineers

    c. APONs

    d. ONUs

3. The passive elements of an EPON are located in the ____________________ (also known as the outside plant) and include single-mode fiber-optic cable, passive optical splitters/couplers, connectors, and splices.

    a. MTUs

    b. optical distribution network

c. customer premises

d. CO chassis

4. The _____________ provides the interface between the EPON system and the service provider's core data, video, and telephony networks.

    a. optical distribution network

    b. customer premises

    c. MTUs

    d. CO chassis

5. Which of the following is a feature or function of the EMS?

    a. supports hundreds of simultaneous GUI users

    b. full FCAPS functionality via a modern graphical user interface (GUI)

    c. capable of managing dozens of fully equipped PON systems

    d. all of the above

6. EPONs can be implemented using either a two-wavelength or a three-wavelength design.

    a. true

    b. false

7. Decreasing growth rates for Ethernet services have confirmed that the telecommunications industry is moving aggressively from Ethernet solutions to a TDM orientation.

    a. true

    b. false

8. EPONs offer the highest bandwidth to customers of any PON system today.

    a. true

    b. false

9. EPON vendors are actively engaged in a new study group known as ______________ that will develop a standard that will apply the proven and widely used Ethernet networking protocol to the access market.

   a. LMA

   b. ITU

   c. EFM

   d. IEEE

Correct Answers

1. Also known as the access network or local loop, the _________________ consists predominantly, in residential areas, of copper telephone wires or coaxial cable television (CATV) cables.

   a. customer premises

   b. hardware

   c. last mile

   d. network

   See Topic 1.

2. ______________ address the shortcomings of point-to-point fiber solutions by using a point-to-multipoint topology instead of point-to-point in the outside plant; by eliminating active electronic components, such as regenerators, amplifiers, and lasers, from the outside plant; and by reducing the number of lasers needed at the CO.

   a. EPONs

   b. Engineers

   c. APONs

   d. ONUs

   See Topic 2.

3. The passive elements of an EPON are located in the _____________________ (also known as the outside plant) and include

single-mode fiber-optic cable, passive optical splitters/couplers, connectors, and splices.

a. MTUs

b. optical distribution network

c. customer premises

d. CO chassis

See Topic 3.

4. The _____________ provides the interface between the EPON system and the service provider's core data, video, and telephony networks.

a. optical distribution network

b. customer premises

c. MTUs

d. CO chassis

See Topic 4.

5. Which of the following is a feature or function of the EMS?

a. supports hundreds of simultaneous GUI users

b. full FCAPS functionality via a modern graphical user interface (GUI)

c. capable of managing dozens of fully equipped PON systems

d. all of the above

See Topic 4.

6. EPONs can be implemented using either a two-wavelength or a three-wavelength design.

a. true

b. false

See Topic 6.

7. Decreasing growth rates for Ethernet services have confirmed that the telecommunications industry is moving aggressively from Ethernet solutions to a TDM orientation.

    a. true

    b. false

    See Topic 8.

8. EPONs offer the highest bandwidth to customers of any PON system today.

    a. true

    b. false

    See Topic 8.

9. EPON vendors are actively engaged in a new study group known as ______________ that will develop a standard that will apply the proven and widely used Ethernet networking protocol to the access market.

    a. LMA

    b. ITU

    c. EFM

    d. IEEE

    See Topic 9.

Glossary

ADM
add/drop multiplexer

APON
asynchronous transfer mode passive optical network

ATM
asynchronous transfer mode

BLEC
building local-exchange carrier

BLSR
bidirectional line-switched ring

CAGR
compound annual growth rate

CATV
cable television

CLEC
competitive local-exchange carrier

CO
central office

CORBA
common object request broker architecture

CSMA/CD
carrier sense multiple access with collision detection

DCS
digital cross-connect

DiffServ
differentiated services

DS
digital signal

DSL
digital subscriber line

DWDM
dense wavelength division multiplexing

EFM
Ethernet in the First Mile [study group]

EMS
element management system

EPON
Ethernet passive optical network

FCAPS
fault, configuration, accounting, performance, and security

FSAN
full-services access network

FTTB
fiber-to-the-building

FTTC
fiber-to-the-curb

FTTH
fiber-to-the-home

GUI
graphical user interface

IEEE
Institute of Electrical and Electronics Engineers

IETF
Internet Engineering Task Force

ILEC
incumbent local-exchange carrier

IP
Internet protocol

IPSec
Internet protocol security

ITU
International Telecommunications Union

ITU–T
ITU–Telecommunications Standardization Sector

LAN
local-area network

MAN
metropolitan-area network

MPEG2
Moving Pictures Experts Group–Layer 2

MSO
multiple-system operator

MTU
multiple-tenant unit

NE
network element

NIM
network interface module

OC
optical carrier

O–E–O
optical-to-electrical-to-optical

OLT
optical line terminal

ONU
optical network unit

OVB
overbuilder

PON
passive optical network

POP
point of presence

POTS
plain old telephone service

PSTN
public switched telephone network

QAM
quadrature amplitude modulation

QoS
quality of service

RF
radio frequency

SCM
switch card module

SDV
switched digital video

SLA
service-level agreement

SONET
synchronous optical network

STS
synchronous transfer mode

TDM
time division multiplex

UPSR
unidirectional path-switched ring

VLAN
virtual local-area network

VOD
video on demand

VoIP
voice over Internet protocol

VPN
virtual private network

WAN
wide-area network

WDM
wavelength division multiplexing