# Digital Subscriber Line

Background

*Digital Subscriber Line (*DSL*)* technology is a modem technology that uses existing twisted-pair telephone lines to transport high-bandwidth data, such as multimedia and video, to service subscribers. The term *xDSL* covers a number of similar yet competing forms of DSL, including ADSL, SDSL, HDSL, RADSL, and VDSL. xDSL is drawing significant attention from implementers and service providers because it promises to deliver high-bandwidth data rates to dispersed locations with relatively small changes to the existing telco infrastructure. xDSL services are dedicated, point-to-point, public network access over twisted-pair copper wire on the local loop ("last mile") between a network service provider (NSP's) central office and the customer site, or on local loops created either intra-building or intra-campus. Currently the primary focus in xDSL is the development and deployment of ADSL and VDSL technologies and architectures. This chapter covers the characteristics and operations of ADSL and VDSL.

Asymmetric Digital Subscriber Line (ADSL)

ADSL technology is asymmetric. It allows more bandwidth downstream—from an NSP's central office to the customer site—than upstream from the subscriber to the central office. This asymmetry, combined with always-on access (which eliminates call setup), makes ADSL ideal for Internet/intranet surfing, video-on-demand, and remote LAN access. Users of these applications typically download much more information than they send.

ADSL transmits more than 6 Mbps to a subscriber, and as much as 640 kbps more in both directions (shown in Figure 15-1). Such rates expand existing access capacity by a factor of 50 or more without new cabling. ADSL can literally transform the existing public information network from one limited to voice, text, and low-resolution graphics to a powerful, ubiquitous system capable of bringing multimedia, including full motion video, to every home this century.

Figure 15-1   The components of a ADSL network include a telco and a CPE.

ADSL Connection
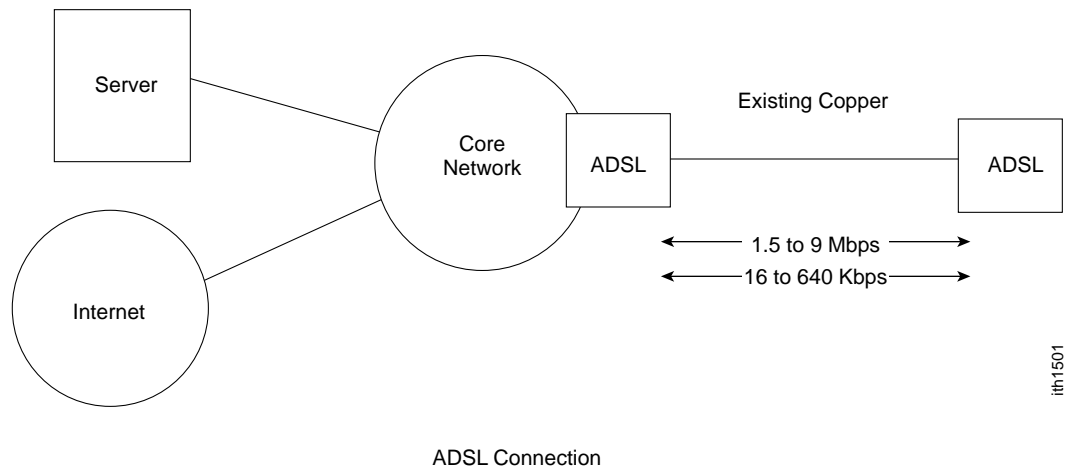
ADSL will play a crucial role over the next decade or more as telephone companies enter new markets for delivering information in video and multimedia formats. New broadband cabling will take decades to reach all prospective subscribers. Success of these new services will depend on reaching as many subscribers as possible during the first few years. By bringing movies, television, video catalogs, remote CD-ROMs, corporate LANs, and the Internet into homes and small businesses, ADSL will make these markets viable and profitable for telephone companies and application suppliers alike.

ADSL Capabilities

An ADSL circuit connects an ADSL modem on each end of a twisted-pair telephone line, creating three information channels—a high-speed downstream channel, a medium-speed duplex channel, and a basic telephone service channel. The basic telephone service channel is split off from the digital modem by filters, thus guaranteeing uninterrupted basic telephone service, even if ADSL fails. The high-speed channel ranges from 1.5 to 6.1 Mbps, and duplex rates range from 16 to 640 kbps. Each channel can be submultiplexed to form multiple lower-rate channels.

ADSL modems provide data rates consistent with North American T1 1.544 Mbps and European E1 2.048 Mbps digital hierarchies (see Figure 15-2) and can be purchased with various speed ranges and capabilities. The minimum configuration provides 1.5 or 2.0 Mbps downstream and a 16 kbps duplex channel; others provide rates of 6.1 Mbps and 64 kbps duplex. Products with downstream rates up to 8 Mbps and duplex rates up to 640 kbps are available today ADSL modems accommodate Asynchronous Transfer Mode (ATM) transport with variable rates and compensation for ATM overhead, as well as IP protocols.

Downstream data rates depend on a number of factors, including the length of the copper line, its wire gauge, presence of bridged taps, and cross-coupled interference. Line attenuation increases with line length and frequency and decreases as wire diameter increases. Ignoring bridged taps ADSL performs as shown in Table 15-1.

Figure 15-2   This chart shows the speeds for downstream bearer and duplex bearer channels.

Downstream Bearer Channels	
n x 1.536 Mbps	1.536 Mbps
	3.072 Mbps
	4.608 Mbps
	6.144 Mbps
n x 2.048 Mbps	2.048 Mbps
	4.096 Mbps
Duplex Bearer Channels	
C Channel	16 Kbps
	64 Kbps
Optional Channels	160 Kbps
	384 Kbps
	544 Kbps
	576 Kbps

24110

Table 15-1   Claimed ADSL Physical-Media Performance

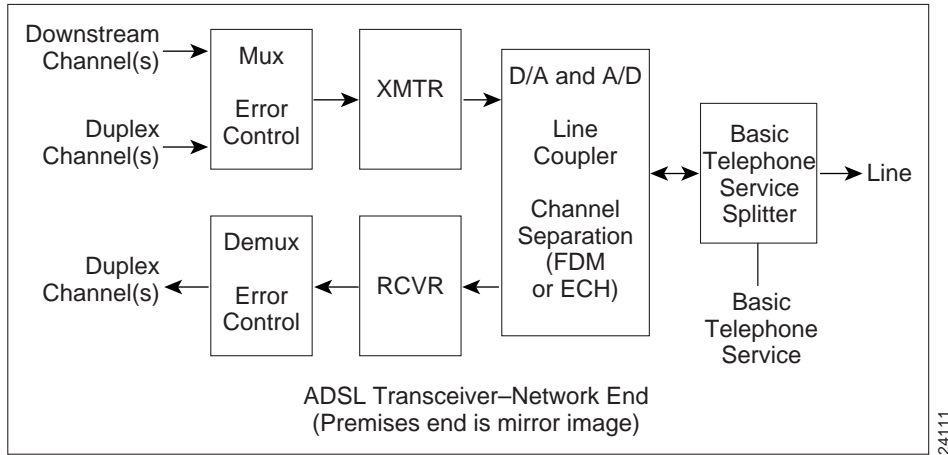| Data rate (Mbps)	Wire gauge (AWG)	Distance (feet)	Wire size (mm)	Distance (kilometers)
1.5 or 2	24	18,000	0.5	5.5
1.5 or 2	26	15,000	0.4	4.6
6.1	24	12,000	0.5	3.7
6.1	26	9,000	0.4	2.7

Although the measure varies from telco to telco, these capabilities can cover up to 95% of a loop plant, depending on the desired data rate. Customers beyond these distances can be reached with fiber-based digital loop carrier (DLC) systems. As these DLC systems become commercially available, telephone companies can offer virtually ubiquitous access in a relatively short time.

Many applications envisioned for ADSL involve digital compressed video. As a real-time signal, digital video cannot use link- or network-level error control procedures commonly found in data communications systems. ADSL modems therefore incorporate forward error correction that dramatically reduces errors caused by impulse noise. Error correction on a symbol-by-symbol basis also reduces errors caused by continuous noise coupled into a line.
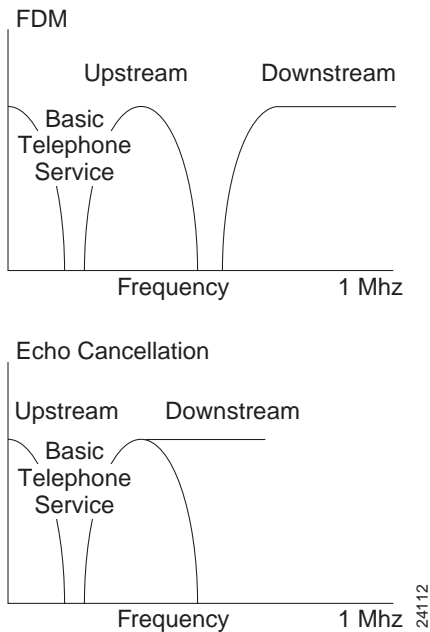
ADSL Technology

ADSL depends on advanced digital signal processing and creative algorithms to squeeze so much information through twisted-pair telephone lines. In addition, many advances have been required in transformers, analog filters, and analog/digital (A/D) converters. Long telephone lines may attenuate signals at 1 MHz (the outer edge of the band used by ADSL) by as much as 90 dB, forcing analog sections of ADSL modems to work very hard to realize large dynamic ranges, separate channels, and maintain low noise figures. On the outside, ADSL looks simple—transparent synchronous data pipes at various data rates over ordinary telephone lines. The inside, where all the transistors work, is a miracle of modern technology. Figure 15-3 displays the ADSL transceiver-network end.

Figure 15-3 **This diagram provides an overview of the devices that make up the ADSL transceiver–network end of the topology.**


```
Downstream
Channel(s)          Mux           XMTR        D/A and A/D
                                               Line                Basic
                    Error                      Coupler          Telephone
Duplex              Control                                       Service      Line
Channel(s)                                     Channel           Splitter
                                              Separation
                    Demux                       (FDM
Duplex                                          or ECH)
Channel(s)          Error         RCVR                            Basic
                    Control                                     Telephone
                                                                 Service
              ADSL Transceiver–Network End
              (Premises end is mirror image)
```

ADSL Transceiver–Network End
(Premises end is mirror image)

24111

To create multiple channels, ADSL modems divide the available bandwidth of a telephone line in one of two ways—frequency-division multiplexing (FDM) or echo cancellation—as shown in Figure 15-4. FDM assigns one band for upstream data and another band for downstream data. The downstream path is then divided by time-division multiplexing into one or more high-speed channels and one or more low-speed channels. The upstream path is also multiplexed into corresponding low-speed channels. Echo cancellation assigns the upstream band to overlap the downstream, and separates the two by means of local echo cancellation, a technique well known in V.32 and V.34 modems. With either technique, ADSL splits off a 4 kHz region for basic telephone service at the DC end of the band.

Figure 15-4 **ADSL uses FDM and echo cancellation to divide the available bandwidth for services.**

FDM

Upstream   Downstream

Basic
Telephone
Service

Frequency   1 Mhz

Echo Cancellation

Upstream   Downstream

Basic
Telephone
Service

Frequency   1 Mhz

24112

An ADSL modem organizes the aggregate data stream created by multiplexing downstream channels, duplex channels, and maintenance channels together into blocks, and attaches an error correction code to each block. The receiver then corrects errors that occur during transmission up to the limits implied by the code and the block length. The unit may, at the user's option, also create superblocks by interleaving data within subblocks; this allows the receiver to correct any combination of errors within a specific span of bits. This in turn allows for effective transmission of both data and video signals.

ADSL Standards and Associations

The American National Standards Institute (ANSI) Working Group T1E1.4 recently approved an ADSL standard at rates up to 6.1 Mbps (ANSI Standard T1.413). The European Technical Standards Institute (ETSI) contributed an annex to T1.413 to reflect European requirements. T1.413 currently embodies a single terminal interface at the premises end. Issue II, now under study by T1E1.4, will expand the standard to include a multiplexed interface at the premises end, protocols for configuration and network management, and other improvements.

The ATM Forum and the Digital Audio-Visual Council (DAVIC) have both recognized ADSL as a physical-layer transmission protocol for UTP media.

The ADSL Forum was formed in December 1994 to promote the ADSL concept and facilitate development of ADSL system architectures, protocols, and interfaces for major ADSL applications. The forum has more than 200 members, representing service providers, equipment manufacturers, and semiconductor companies throughout the world. At present, the Forum's formal technical work is divided into the following six areas, each of which is dealt with in a separate working group within the technical committee:

- ATM over ADSL (including transport and end-to-end architecture aspects)
- Packet over ADSL (this working group recently completed its work)
- CPE/CO (customer premises equipment/central office) configurations and interfaces
- Operations
- Network management
- Testing and interoperability

ADSL Market Status

ADSL modems have been tested successfully in more than 30 telephone companies, and thousands of lines have been installed in various technology trials in North America and Europe. Several telephone companies plan market trials using ADSL, principally for data access, but also including video applications for uses such as personal shopping, interactive games, and educational programming.

Semiconductor companies have introduced transceiver chipsets that are already being used in market trials. These chipsets combine off-the-shelf components, programmable digital signal processors, and custom ASICs (application-specific integrated circuits). Continued investment by these semiconductor companies has increased functionality and reduced chip count, power consumption, and cost, enabling mass deployment of ADSL-based services.

Very-High-Data-Rate Digital Subscriber Line (VDSL)

It is becoming increasingly clear that telephone companies around the world are making decisions to include existing twisted-pair loops in their next-generation broadband access networks. Hybrid fiber coax (HFC), a shared-access medium well suited to analog and digital broadcast, comes up somewhat short when used to carry voice telephony, interactive video, and high-speed data communications at the same time. Fiber all the way to the home (FTTH) is still prohibitively expensive in a marketplace soon to be driven by competition rather than cost. An attractive alternative, soon to be commercially practical, is a combination of fiber cables feeding neighborhood optical network units (ONUs) and last-leg-premises connections by existing or new copper. This topology, which is often called fiber to the neighborhood (FTTN), encompasses fiber to the curb (FTTC) with short drops and fiber to the basement (FTTB), serving tall buildings with vertical drops.

One of the enabling technologies for FTTN is VDSL. In simple terms, VDSL transmits high-speed data over short reaches of twisted-pair copper telephone lines, with a range of speeds depending on actual line length. The maximum downstream rate under consideration is between 51 and 55 Mbps over lines up to 1000 feet (300 m) in length. Downstream speeds as low as 13 Mbps over lengths beyond 4000 feet (1500 m) are also common. Upstream rates in early models will be asymmetric, just like ADSL, at speeds from 1.6 to 2.3 Mbps. Both data channels will be separated in frequency from bands used for basic telephone service and Integrated Services Digital Network (ISDN), enabling service providers to overlay VDSL on existing services. At present the two high-speed channels are also separated in frequency. As needs arise for higher-speed upstream channels or symmetric rates, VDSL systems may need to use echo cancellation.

Figure 15-5   This diagram provides an overview of the devices in a VDSL network.
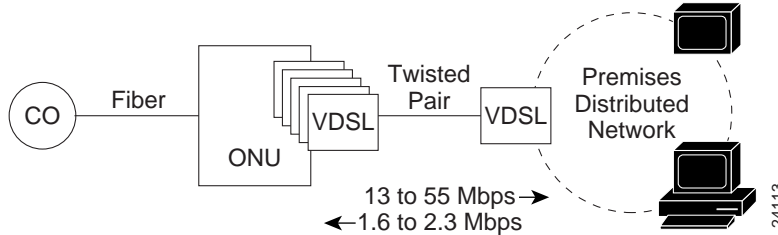
VDSL Projected Capabilities

Although VDSL has not achieved ADSL's degree of definition, it has advanced far enough that we can discuss realizable goals, beginning with data rate and range. Downstream rates derive from submultiples of the SONET (Synchronous Optical Network) and SDH (Synchronous Digital Hierarchy) canonical speed of 155.52 Mbps, namely 51.84 Mbps, 25.92 Mbps, and 12.96 Mbps. Each rate has a corresponding target range:

Target Range (Mbps)	Distance (feet)	Distance (meters)
12.96–13.8	4500	1500
25.92–27.6	3000	1000
51.84–55.2	1000	300

Upstream rates under discussion fall into three general ranges:

- 1.6–2.3 Mbps.

- 19.2 Mbps

- Equal to downstream

Early versions of VDSL will almost certainly incorporate the slower asymmetric rate. Higher upstream and symmetric configurations may only be possible for very short lines. Like ADSL, VDSL must transmit compressed video, a real-time signal unsuited to error retransmission schemes used in data communications. To achieve error rates compatible with those of compressed video, VDSL will have to incorporate forward error correction (FEC) with sufficient interleaving to correct all errors created by impulsive noise events of some specified duration. Interleaving introduces delay, on the order of 40 times the maximum length correctable impulse.

Data in the downstream direction will be broadcast to every CPE on the premises or be transmitted to a logically separated hub that distributes data to addressed CPE based on cell or time-division multiplexing (TDM) within the data stream itself. Upstream multiplexing is more difficult. Systems using a passive network termination (NT) must insert data onto a shared medium, either by a form of TDM access (TDMA) or a form of frequency-division multiplexing (FDM). TDMA may use a species of token control called cell grants passed in the downstream direction from the ONU modem, or contention, or both (contention for unrecognized devices, cell grants for recognized devices). FDM gives each CPE its own channel, obviating a Media Access Control (MAC) protocol, but either limiting data rates available to any one CPE or requiring dynamic allocation of bandwidth and inverse multiplexing at each CPE. Systems using active NTs transfer the upstream collection problem to a logically separated hub that would use (typically) Ethernet or ATM protocols for upstream multiplexing.

Migration and inventory considerations dictate VDSL units that can operate at various (preferably all) speeds with automatic recognition of a newly connected device to a line or a change in speed. Passive network interfaces need to have hot insertion, where a new VDSL premises unit can be put on the line without interfering with the operation of other modems.

VDSL Technology

VDSL technology resembles ADSL to a large degree, although ADSL must face much larger dynamic ranges and is considerably more complex as a result. VDSL must be lower in cost and lower in power, and premises VDSL units may have to implement a physical-layer MAC for multiplexing upstream data.

Line Code Candidates

Four line codes have been proposed for VDSL:

- *CAP (carrierless amplitude modulation/phase modulation)*—A version of suppressed carrier quadrature amplitude modulation (QAM). For passive NT configurations, CAP would use quadrature phase shift keying (QPSK) upstream and a type of TDMA for multiplexing (although CAP does not preclude an FDM approach to upstream multiplexing).

- *DMT (discrete multitone)*—A multicarrier system using discrete fourier transforms to create and demodulate individual carriers. For passive NT configurations, DMT would use FDM for upstream multiplexing (although DMT does not preclude a TDMA multiplexing strategy).

- *DWMT (discrete wavelet multitone)*—A multicarrier system using wavelet transforms to create and demodulate individual carriers. DWMT also uses FDM for upstream multiplexing, but also allows TDMA.

- *SLC (simple line code)*—A version of four-level baseband signaling that filters the based band and restores it at the receiver. For passive NT configurations, SLC would most likely use TDMA for upstream multiplexing, although FDM is possible.

Channel Separation

Early versions of VDSL will use frequency division multiplexing to separate downstream from upstream channels and both of them from basic telephone service and ISDN (shown in Figure 15-6). Echo cancellation may be required for later-generation systems featuring symmetric data rates. A rather substantial distance, in frequency, will be maintained between the lowest data channel and basic telephone service to enable very simple and cost-effective basic telephone service splitters. Normal practice would locate the downstream channel above the upstream channel. However, the DAVIC specification reverses this order to enable premises distribution of VDSL signals over coaxial cable systems.

Figure 15-6   Early versions of VDSL will use FDM to separate downstream from upstream channels and both of them from basic telephone service and ISDN, as this example shows.
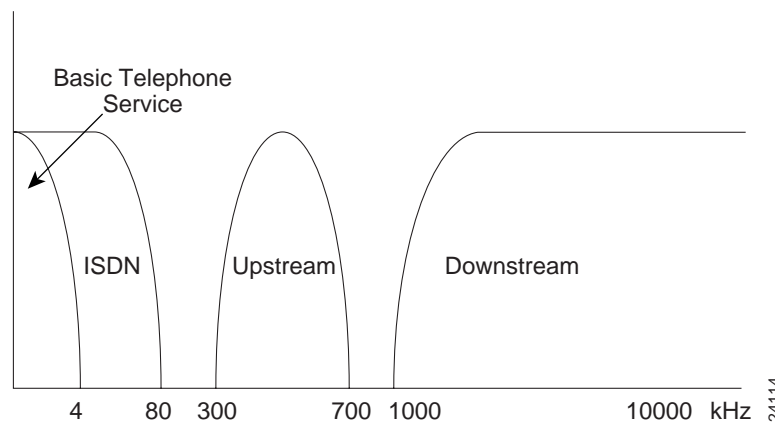
Forward Error Control

FEC will no doubt use a form of Reed Soloman coding and optional interleaving to correct bursts of errors caused by impulse noise. The structure will be very similar to ADSL, as defined in T1.413. An outstanding question is whether FEC overhead (in the range of 8%) will be taken from the payload capacity or added as an out-of-band signal. The former reduces payload capacity but maintains nominal reach, whereas the latter retains the nominal payload but suffers a small reduction in reach. ADSL puts FEC overhead out of band.
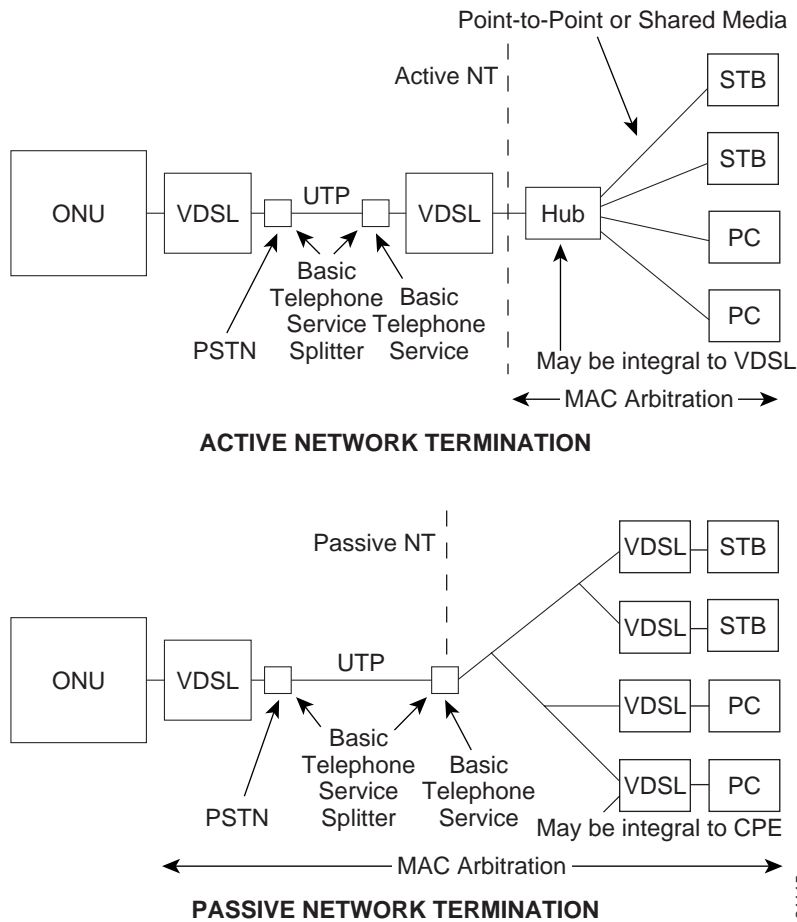
Upstream Multiplexing

If the premises VDSL unit comprises the network termination (an active NT), then the means of multiplexing upstream cells or data channels from more than one CPE into a single upstream becomes the responsibility of the premises network. The VDSL unit simply presents raw data streams in both directions. As illustrated in Figure 15-7, one type of premises network involves a star connecting each CPE to a switching or multiplexing hub; such a hub could be integral to the premises VDSL unit.

In a passive NT configuration, each CPE has an associated VDSL unit. (A passive NT does not conceptually preclude multiple CPE per VDSL, but then the question of active versus passive NT becomes a matter of ownership, not a matter of wiring topology and multiplexing strategies.) Now the upstream channels for each CPE must share a common wire. Although a collision-detection system could be used, the desire for guaranteed bandwidth indicates one of two solutions. The first invokes a cell-grant protocol in which downstream frames generated at the ONU or farther up the network contain a few bits that grant access to specific CPE during a specified period subsequent to receiving a frame. A granted CPE can send one upstream cell during this period. The transmitter in the CPE must turn on, send a preamble to condition the ONU receiver, send the cell, and then turn itself off. The protocol must insert enough silence to let line ringing clear. One construction of this protocol uses 77 octet intervals to transmit a single 53-octet cell.

Figure 15-7   This figure shows examples of termination methods in passive and active networks.

ACTIVE NETWORK TERMINATION

PASSIVE NETWORK TERMINATION

The second method divides the upstream channel into frequency bands and assigns one band to each CPE. This method has the advantage of avoiding any MAC with its associated overhead (although a multiplexor must be built into the ONU), but either restricts the data rate available to any one CPE or imposes a dynamic inverse multiplexing scheme that lets one CPE send more than its share for a period. The latter would look a great deal like a MAC protocol, but without the loss of bandwidth associated with carrier detect and clear for each cell.

VDSL Issues

VDSL is still in the definition stage; some preliminary products exist, but not enough is known yet about telephone line characteristics, radio frequency interface emissions and susceptibility, upstream multiplexing protocols, and information requirements to frame a set of definitive, standardizable properties. One large unknown is the maximum distance that VDSL can reliably realize for a given data rate. This is unknown because real line characteristics at the frequencies required for VDSL are speculative, and items such as short bridged taps or unterminated extension lines in homes, which have no effect on telephony, ISDN, or ADSL, may have very detrimental affects on VDSL in certain configurations. Furthermore, VDSL invades the frequency ranges of amateur radio, and every above-ground telephone wire is an antenna that both radiates and attracts energy in amateur radio bands. Balancing low signal levels to prevent emissions that interfere with amateur radio with higher signals needed to combat interference by amateur radio could be the dominant factor in determining line reach.

A second dimension of VDSL that is far from clear is the services environment. It can be assumed that VDSL will carry information in ATM cell format for video and asymmetric data communications, although optimum downstream and upstream data rates have not been ascertained. What is more difficult to assess is the need for VDSL to carry information in non-ATM formats (such as conventional Plesiochronous Digital Hierarchy [PDH] structures) and the need for symmetric channels at broadband rates (above T1/E1). VDSL will not be completely independent of upper-layer protocols, particularly in the upstream direction, where multiplexing data from more than one CPE may require knowledge of link-layer formats (that is, ATM or not).

A third difficult subject is premises distribution and the interface between the telephone network and CPE. Cost considerations favor a passive network interface with premises VDSL installed in CPE and upstream multiplexing handled similarly to LAN buses. System management, reliability, regulatory constraints, and migration favor an active network termination, just like ADSL and ISDN, that can operate like a hub, with point-to-point or shared-media distribution to multiple CPE on-premises wiring that is independent and physically isolated from network wiring.

However, costs cannot be ignored. Small ONUs must spread common equipment costs, such as fiber links, interfaces, and equipment cabinets, over a small number of subscribers compared to HFC. VDSL therefore has a much lower cost target than ADSL because VDSL may connect directly from a wiring center or cable modems, which also have much lower common equipment costs per user. Furthermore, VDSL for passive NTs may (only *may*) be more expensive than VDSL for active NTs, but the elimination of any other premises network electronics may make it the most cost-effective solution, and highly desired, despite the obvious benefits of an active NT. Stay tuned.

Standards Status

At present five standards organizations/forums have begun work on VDSL:

- *T1E1.4*—The U.S. ANSI standards group T1E1.4 has just begun a project for VDSL, making a first attack on system requirements that will evolve into a system and protocol definition.

- *ETSI*—The ETSI has a VDSL standards project, under the title High-Speed Metallic Access Systems, and has compiled a list of objective, problems, and requirements. Among its preliminary findings are the need for an active NT and payloads in multiples of SDH virtual container VC-12, or 2.3 Mbps. ETSI works very closely with T1E1.4 and the ADSL Forum, with significant overlapping attendees.

- *DAVIC*—DAVIC has taken the earliest position on VDSL. Its first specification due to be finalized will define a line code for downstream data, another for upstream data, and a MAC for upstream multiplexing based on TDMA over shared wiring. DAVIC is only specifying VDSL for

a single downstream rate of 51.84 Mbps and a single upstream rate of 1.6 Mbps over 300 m or less of copper. The proposal assumes, and is driven to a large extent by, a passive NT, and further assumes premises distribution from the NT over new coaxial cable or new copper wiring.

- *The ATM Forum*—The ATM Forum has defined a 51.84 Mbps interface for private network UNIs and a corresponding transmission technology. It has also taken up the question of CPE distribution and delivery of ATM all the way to premises over the various access technologies described above.

- *The ADSL Forum*—The ADSL Forum has just begun consideration of VDSL. In keeping with its charter, the forum will address network, protocol, and architectural aspects of VDSL for all prospective applications, leaving line code and transceiver protocols to T1E1.4 and ETSI and higher-layer protocols to organizations such as the ATM Forum and DAVIC.

VDSL's Relationship with ADSL

VDSL has an odd technical resemblance to ADSL. VDSL achieves data rates nearly 10 times greater than those of ADSL (shown in Figure 15-8), but ADSL is the more complex transmission technology, in large part because ADSL must contend with much larger dynamic ranges than VDSL. However, the two are essentially cut from the same cloth. ADSL employs advanced transmission techniques and forward error correction to realize data rates from 1.5 to 9 Mbps over twisted pair, ranging to 18,000 feet; VDSL employs the same advanced transmission techniques and forward error correction to realize data rates from 13 to 55 Mbps over twisted pair, ranging to 4,500 feet. Indeed, the two can be considered a continuum, a set of transmission tools that delivers about as much data as theoretically possible over varying distances of existing telephone wiring.

Figure 15-8   This chart provides a comparison of transfer rates between ADSL and VDSL.
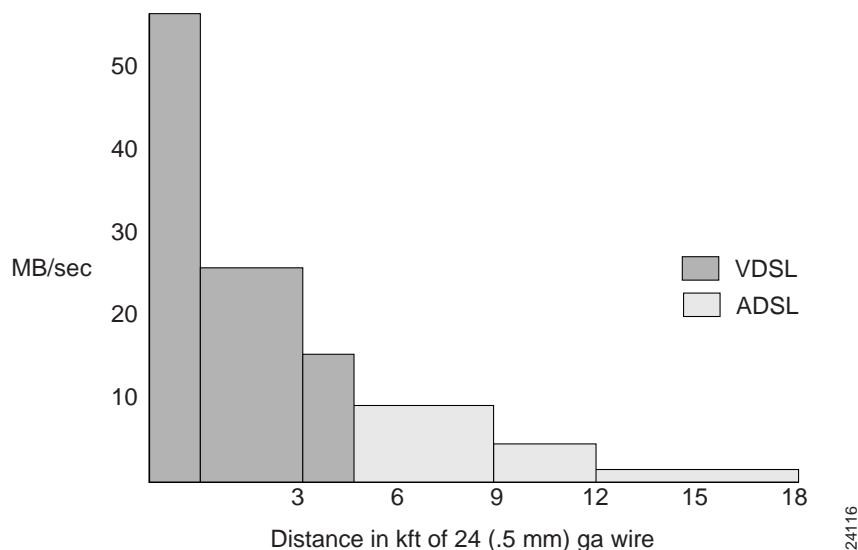
VDSL is clearly a technology suitable for a full-service network (assuming that *full service* does not imply more than two high-definition television [HDTV] channels over the highest-rate VDSL). It is equally clear that telephone companies cannot deploy ONUs overnight, even if all the technology were available. ADSL may not be a full-service network technology, but it has the singular advantage of offering service over lines that exist today, and ADSL products are closer in time than VDSL. Many new services being contemplated today—such as videoconferencing, Internet access, video on demand, and remote LAN access—can be delivered at speeds at or below T1/E1 rates. For such services, ADSL/VDSL provides an ideal combination for network evolution. On the longest

lines, ADSL delivers a single channel. As line length shrinks, either from natural proximity to a central office or deployment of fiber-based access nodes, ADSL and VDSL simply offer more channels and capacity for services that require rates above T1/E1 (such as digital live television and virtual CD-ROM access).