5

Introduction to DSL

Edward Jones

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ABSTRACT This chapter introduces some of the technologies that are used in DSL systems to try to realize the information-transmission potential of twisted-pair lines, and also briefly describes the different varieties of DSL that are in use or are under development. The motivation for the development of DSL services and technology is considered; in particular, alternative access technologies are reviewed, following which the different varieties of DSL are discussed in order to set the context for later chapters.

5.1 Introduction

Previous chapters of this book have discussed the fundamentals of the copper access network: its architecture, characteristics, and in particular how the transmission channel affects a signal. In addition, Chapter 3 described in detail how the signal is degraded by noise and interference from various sources (crosstalk, impulse noise, etc.). Some fundamental limits on the data-carrying capacity of the copper access network were presented in Chapter 4. The present chapter introduces some of the technologies that are used in DSL systems and briefly describes the varieties of DSL that are in use or are under development. In addition, simple block diagrams for DSL transceivers are presented, highlighting the various subsystems required and how these are used to compensate for the various sources of signal distortion described in previous chapters. Many of these subsystems are described in considerable detail in later chapters.

The focus of this chapter is very much on physical layer aspects of DSL transmission systems; later chapters will describe end-to-end system architectures that utilize DSL transmission systems, and will outline how the DSL physical layer interacts with high layers to realize useful services. Furthermore, the intention here is not to go into exhaustive detail on the different DSL standards; this is covered in Volume 2 of this series (and in many other books and papers already published, for example [Starr 1999][Starr 2003] and references therein). Rather, the intention is to give the reader a basic overview of DSL, and to set the context for the chapters that follow.

5.2 History

This section is intended to briefly summarize the various transmission technologies that have been deployed on the telephone network. For a detailed description of this network, the reader is referred to Section 1.1. The public switched telephone network (PSTN) was originally designed to carry voice signals, and the bandwidth of these signals was limited to the frequency range from approximately 200 Hz to 3.4 kHz (with some variations, depending on location). Although a voice signal is analog by its nature, digitization of many of the links in the telephone network is very common now (as explained in Chapter 1), particularly in the trunk network between telephone company central offices (COs), which is heavily based on optical fiber and microwave links. For the most part, a voice signal travels in analog form from the originating user to the local CO across a copper twisted pair (the local loop), where it is digitized by a codec ("coder/decoder"), following which it is transmitted over the trunk network to the CO serving the user at the other end. Here it is converted from digital form back to analog by another codec, before being transmitted across this user's local loop to the receiving telephone.

The 1950s saw the introduction of voiceband modems for the purpose of transmitting data across the PSTN. Early modems (for example, the Bell 103) transmitted at low bit rates (300 bits per second (bit/s)) using frequency shift keying (FSK) modulation. Modem technology quickly developed to provide higher bit rates and also enabled full-duplex transmission. For example, the CCITT (now ITU-T) V.22 standard provided for communication at 1200 bit/s, and the later V.22bis recommendation extended this to 2400 bit/s. Subsequent developments led to V.32 (9600 bit/s), V.32bis (14, 400 bit/s), and later V.34, which uses very sophisticated signal processing techniques to achieve bit rates up to 33.6 kbit/s, with various fall-back options. In the late 1990s, pulse coded modulation (PCM) modems were developed and standardized as ITU-T Recommendation V.90. This recommendation provides for up to 56 kbit/s in the downstream direction (from the CO to the user), where an all-digital path is assumed to exist between the data source and the CO serving the user. This is a reasonable assumption in practice, because many information sources, such as Internet service providers (ISPs), have direct digital connections to the PSTN. In V.90, the upstream direction of transmission uses V.34 modulation, limiting upstream bandwidth to 33.6 kbit/s. A good overview of the technologies used in voiceband modems may be found in [Forney 1984] [Forney 1996] [Ayanoglu 1998]. Figure 5.1(a) shows a block diagram of a typical voiceband modem communication link, and Figure 5.1(b) shows a link using a V.90 modem.

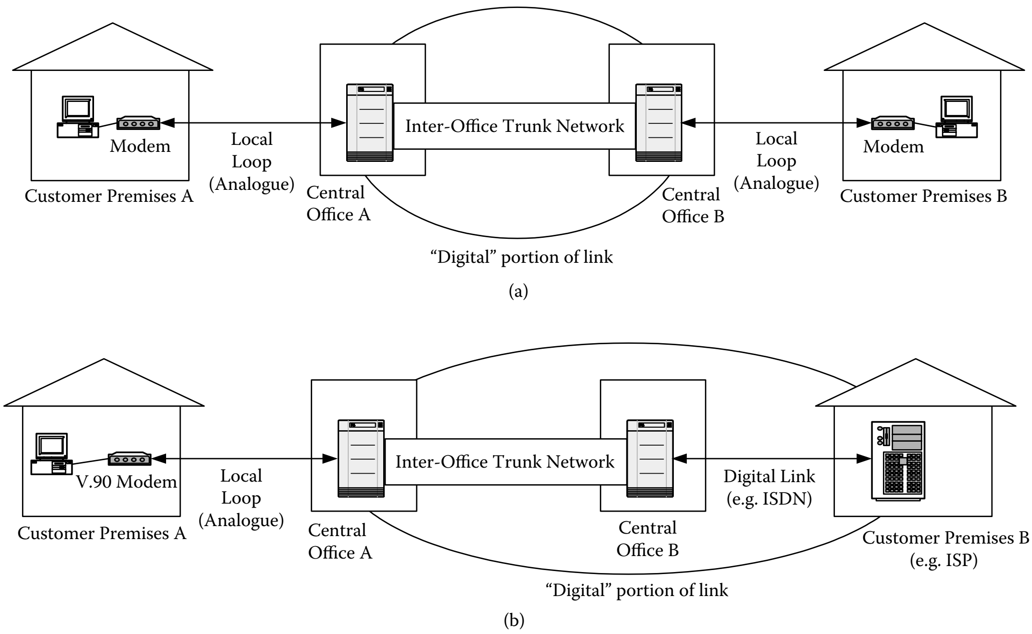

FIGURE 5.1
(a) Conceptual block diagram of a typical voiceband modem link (pre-V.90); (b) block diagram of a V.90 modem link, indicating the all-digital link between (for example) an ISP and the serving central office.

Voiceband modems continue to push the limits of the technology; however, there is a limit to what is achievable within the existing PSTN framework with its limited bandwidth (although, given the remarkable advances in voiceband modem technology over the years, it may not be entirely clear where this limit lies). At the same time, users (both residential and commercial) continue to demand ever-increasing bit rates for many different applications, so the local loop of the PSTN as it stands has essentially become a bottleneck. Residential users demand faster transmission rates for Internet access, and the multitude of applications it enables (Web browsing, e-mail, online shopping and gaming, and many other applications). Typically, the traffic pattern for residential users is asymmetric, in the sense that applications like Web browsing generally demand higher bit rates in the downstream direction than in the upstream direction. Business users, particularly of the small office-home office (SOHO) variety, also need faster access for remote office connectivity, LAN-extension, file sharing, video-conferencing, etc. In this case, the bit rate requirements tend to be more symmetric, because remotely located business customers often tend to transmit as much as they receive.

These user requirements for higher-speed local access have driven the need for transmission systems capable of providing transmission speeds of hundreds of kilobits, or even megabits, per second. The next subsection briefly introduces some of the access mechanisms that may be used to achieve this, including DSL.

5.3 Alternative Broadband Access Technologies

5.3.1 Fiber

It is generally accepted that the ultimate goal in local access is the provision of fiber-optic transmission to every user, so-called Fiber-to-the-home (FTTH) (with this term implicitly encompassing Fiber-to-the-business as well). A common architecture for deploying fiber-based communications is the passive optical network (PON), which has a single transceiver in the CO serving multiple customers, with splitters and couplers to distribute the service among the different subscribers.[1]

Although FTTH would satisfy the bandwidth requirements of even the most demanding user, this scenario is unlikely to be achieved for some considerable time to come. The reason is, quite simply, the cost involved in the installation of an FTTH network (particularly labor and other nonequipment costs), costs that would be extremely difficult for the service provider to recover in a reasonable time frame.

However, as was mentioned in Section 1.1, although the goal of FTTH for all users is still some way off, some progress toward this end is being made. For example, it is common for fiber to be deployed to serve new offices and residential buildings and developments, and to replace an existing telephony plant that has reached the end of its useful life. This encompasses both fiber deployments directly to the home, as well as to intermediate points in the distribution network, for example, at the end of a residential street. This type of architecture is often referred to as Fiber-to-the-curb or Fiber-to-the-cabinet. As a half-way point to full FTTH, these installations are capable of serving many subscribers with a single fiber, and effectively reducing the distance over which subscribers need to be served by means of other access technologies (including DSL, as will be described later). Some further information on optical fiber access may be found in [Cramer 2002] and [IEEE Com. Mag. Dec. 2001].

[1] An alternative is point-to-point, whereby each subscriber has a dedicated optical transceiver at the CO.

An interesting variation on this theme is the development of systems for optical wireless (or free-space optical) transmission for local access; see, for example, [IEEE Com. Mag. March 2003].

5.3.2 Wireless

Wireless remote access comes in a number of different variations [Boelcskei 2001] [IEEE Com. Mag. 2002] [IEEE Com. Mag. Sept. 2001], which are sometimes generically referred to as wireless local loop (WLL). Wireless may seem like the obvious choice for a (fixed-position) local access technology, because it does not require the installation of a transmission medium. This can be particularly important in developing countries, where the level of installed communications infrastructure significantly lags behind that in developed countries. However, there are a number of issues that have hampered the deployment of wireless local access. For example, the available radio spectrum is becoming increasingly congested, forcing broadband wireless access systems to move to higher frequencies, where line-of-sight (LOS) operation may become necessary. This applies, for example, with the local multi-point distribution system (LMDS) and similar systems operating between 20 and 40 GHz. Furthermore, there are still challenges and costs associated with deploying the necessary infrastructure where it is required, for example, planning issues associated with location of base stations, as well as the challenge of developing user-friendly customer premises equipment (CPE).

Systems operating at lower frequencies, where non-LOS transmission is more reliable, have also been deployed (*e.g.*, microwave multi-point distribution system (MMDS) in the region of 2–4 GHz), though greater bandwidth efficiency may be required to increase bit rates. On the other hand, fading and multi-path propagation make it more difficult to use higher-order modulation to achieve the necessary spectral efficiency. At the same time, the fact that the transmitter and receiver are in fixed locations means that directional (and multiple) antennae may be used to increase performance.

A related area of standards development is the so-called wireless metropolitan area network (wireless MAN), currently under the auspices of IEEE Working Group 802.16 [IEEE 802.16].

5.3.3 Cable Modem

For many years, coaxial cable has been used to distribute television services to subscribers. It was quickly realized that this same medium could also be used to carry broadband data and even voice, and so represented another means of broadband access. However, much of the cable network is unidirectional, in the sense that it was originally intended for broadcast applications (*i.e.*, cable TV delivery). In recent times however, large portions of the cable infrastructure have been made bidirectional, in order to allow for two-way transmission. A typical architecture consists of fiber-optic cable carrying signals between the cable head-end and fiber nodes in the network, from which existing coaxial cable is used to cover the "last mile" to the subscribers' premises. This architecture is generally referred to as hybrid fiber-coax (HFC) and is illustrated in Figure 5.2. A special cable modem is used to terminate the connection in the subscriber premises. The need for interoperability between cable modem equipment from different vendors resulted in the development of the Data over Cable Service Interface Specifications (DOCSIS).

Quadrature amplitude modulation (QAM) (see Chapter 6) is commonly used for cable modem transmission in the downstream direction. Using 64-QAM, a single 6 MHz analog channel originally used for cable TV transmission is capable of carrying around 30 Mbit/s (allowing for roll-off of the signal spectrum and also allowing for a guard band between

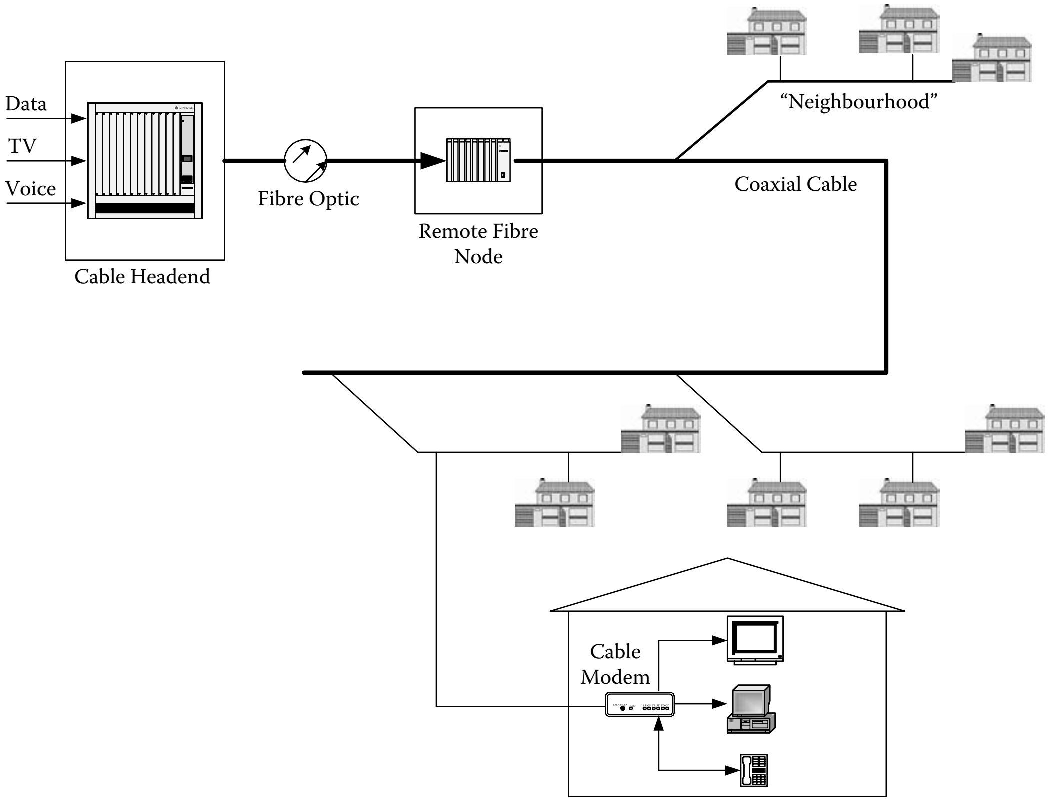

FIGURE 5.2
Simplified representation of Hybrid Fiber Coax architecture for broadband access.

channels). Increasing the number of QAM levels to 256 would increase the data-carrying capacity of each channel to around 40 Mbit/s. In the downstream direction, the signal (consisting of a combination of data, TV, and perhaps voice) is converted into an optical signal and carried by optical fiber to a "fiber node" in the distribution network. At this point it is converted to an electrical signal, and distributed to subscribers using the existing coaxial cable. The cable modem separates the composite received signal into its various components (for example, Internet data, voice, and TV) and distributes them to their respective destinations (PC, telephone, TV set). In the upstream direction, lower-order modulation, for example, quaternary phase shift keying (QPSK), is typically used. This has lower spectral efficiency than 64- or 256-QAM, but it is more robust and better able to deal with the harsh conditions to which the upstream signal is subjected. In any case, the asymmetric bandwidth requirements of applications such as Internet access mean that a lower bit rate can be tolerated in the upstream direction.

One of the problems associated with HFC for broadband data access is the cost associated with converting the existing cable network from unidirectional to bidirectional operation, in particular, provision of bidirectional amplifiers and related equipment. A further problem is the fact that HFC is a shared medium; that is, all of the available bandwidth is shared among all of the subscribers served by a particular fiber node. As more subscribers join the network, the bandwidth available to any single subscriber decreases.

Further details on cable access and HFC technology may be found in [IEEE Com. Mag. June 2001] .

5.3.4 Power Line Communications

A recent development in the broadband access field is the use of the electric power supply network for the transmission of broadband data. One of the major motivations for this approach is (as explained in the abstract to Chapter 1) the ubiquitous nature of this network. In addition to using the electricity supply network for access, there is also the possibility of using existing in-home electric wiring as a form of local area network (LAN) in the home. However, a number of technical issues still need to be fully addressed, including the design of systems able to perform well in the very harsh environment of this network, regulatory issues, and issues relating to safety. An overview of initial developments in this area may be found in [IEEE Com. Mag. May 2003].

5.3.5 Digital Subscriber Lines

Although there are several other media that can be used to provide broadband access to residential and business subscribers, none of them has the ubiquity (or the level of maturity of development) of the telephone network. Telephony service is provided to almost every business and residential subscriber in most of the world, with several hundred million twisted-pair telephone lines installed globally to date. Furthermore, as discussed in Chapter 4, the data-carrying capacity of telephone twisted pairs greatly exceeds what is currently achievable with voiceband modem technology.

The next section of this chapter briefly describes the different varieties of DSL technology, and the following section introduces some of the details of the physical layers of these systems. Chapters 6 and 7 provide additional detail on the physical layers used in DSL.

5.4 Overview of DSL Technology

5.4.1 Introduction

The range of DSL technologies is quite broad, and this breadth can be somewhat confusing to the uninitiated. This section briefly describes the different types of DSL technology that have been developed or are currently under development. Much of this development has taken place in various regional and global standards committees, for example, ANSI committee T1E1.4 (Digital Subscriber Loop Access), ETSI Working Group TM6 (Transmission and Multiplexing), and ITU-T Study Group 15/Question 4, as well as in-industry forums such as the DSL Forum. The work of the various standards committees will be described in more detail in Volume 2 of this series.

In simple terms, DSL technologies can be subdivided into two broad classes:

- **Symmetric**. Within this class, the data rate transmitted in both directions (downstream and upstream) is the same. This is a typical requirement of business customers.
- **Asymmetric**. In this case, there is asymmetry between the data rates in the downstream and upstream directions, with the downstream data rate typically higher than the upstream (usually appropriate for applications such as Web browsing).

This division is quite crude however, and, to confuse matters, some of the various technologies are capable of both asymmetric and symmetric operation. To further complicate things, many DSL systems are capable of multi-rate operation, which adds a further dimension of variability.

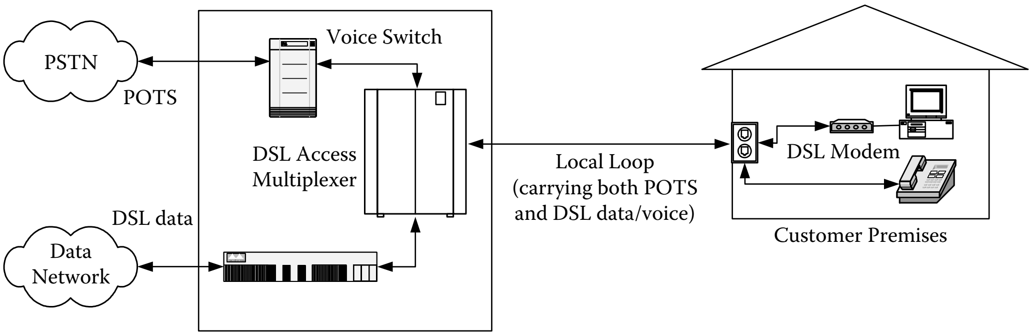

FIGURE 5.3
Block diagram of "generic" DSL reference model. It should be noted that DSL is an "overlay" on the existing switched telephone network.

An additional point to note is that symmetric DSLs generally use baseband modulation such as pulse amplitude modulation (PAM) (see Section 6.2.2), where the bandwidth of the transmitted signal extends all the way down to 0 Hz (notwithstanding the effect of any coupling transformers or other filtering), whereas the asymmetric technologies generally use passband modulation, which avoids the lowest frequencies that would be used by voiceband services such as analog telephony (see Chapters 6 and 7 for further information on digital modulation techniques). This is generally because the residential users who would typically make use of asymmetric DSLs still need to be able to make use of "lifeline" POTS, even when the DSL service is unavailable (for example, due to a power failure in the customer premises). Provision of lifeline POTS service is generally less of an issue for business users, who might typically carry all of their business voice traffic on the DSL link anyway.

A block diagram of a typical DSL configuration is shown in Figure 5.3. Note that the term "digital subscriber line" generally refers to the analog local loop between each customer premises and its local central office, and a DSL modem is required at each end of the loop. Furthermore, the DSL service can be regarded as being provided by means of an "overlay" network that is not part of the normal switched telephone network. This means that the service provider CO needs to be able to separate the DSL service from the POTS service, with the voice service being sent onward by means of the ordinary trunk network, whereas the data carried by the DSL may be sent to a data network that is separate from the switched voice network. The CO will generally provide DSL service to the user premises using a DSL access multiplexer (DSLAM), which is described in Volume 2 in this series. The DSLAM usually contains many DSL modems serving multiple customers.

A block diagram of a typical DSL configuration is shown in Figure 5.3: the key point to note here is that in essence, a "digital subscriber line" exists on a *single* local loop between the customer premises and the central office, unlike the voiceband modem case where, technically, the modem link includes *two* local loops (plus the network elements in between). Furthermore, the DSL service can be regarded as being provided by means of an "overlay" network that is not part of the normal switched telephone network. This means that the service provider central office needs to be able to separate the DSL service from the POTS service, with the voice service being sent onward by means of the ordinary trunk network, whereas the data carried by the DSL may be sent to a data network that is separate from the switched voice network. The CO will generally provide DSL service to the user premises using a DSL access multiplexer, which is described in Volume 2 in this series.

Generally speaking, before they can be used for the transmission of user data, DSL transceivers must go through an activation phase, whereby various receiver (and transmitter) elements must be initialized. In particular, the receiver functional blocks (equalizer, timing recovery, etc.) must be adapted so that reliable communication can take place under the particular loop and noise conditions at the time. The details of these functional blocks are covered in upcoming chapters.

In some cases, when DSL systems have a number of possible configurations to choose from (for example, multiple bit rates), the activation phase is also used to allow the transceivers on either end of the line to agree on what configuration they will use, through a session of "handshaking."

In the interest of simplicity, the description given here will follow a broadly "historical" approach, with reference made to the above classifications where appropriate. This section will merely introduce the various DSL technologies, and the following section will introduce functional block diagrams of the physical layers of different categories of systems. Subsequent chapters discuss the different blocks in some detail. Volume 2 includes details and features of specific standards for DSL (some of which are referred to in passing in this chapter).

5.4.2 Performance Requirements of DSL Systems

In a practical sense, all varieties of DSL have a specified environment in which they are expected to operate reliably. This specified environment includes the types of loops over which the service is expected to operate, as well as a definition of the expected noise environment (including impulse noise and crosstalk). DSL technologies that have been developed in recent times are also expected to be spectrally compatible with services already in use in the loop plant, in the sense that the presence of the new DSL will not unduly degrade the performance of existing services.

Chapters 6 and 7 provide detailed descriptions of the modulation techniques most commonly used in DSL systems; in particular, the signal-to-noise ratio (SNR) required for these modulation techniques to operate with some specific probability of error is discussed in detail. These SNR requirements impose fundamental performance limits that can be achieved in practical DSL systems.

Basic DSL performance requirements are usually specified in terms of acceptable bit error ratio (BER) with specified noise margin while operating in certain conditions. The BER usually used in DSL development is 10^{-7}, and the noise margin is usually either 5 or 6 dB. The noise margin specification means that the system is expected to operate at an actual BER no greater than the specified BER when the noise is increased by a level equal to the noise margin. Typically, the specified test conditions mirror anticipated worst-case conditions. The inclusion of the noise margin means that DSL systems generally operate in normal conditions with BER much less than 10^{-7}, and it also allows for reliable operation when the noise conditions are worse than normal (*e.g.*, due to the presence of unexpected sources of noise).

The next few subsections largely deal with symmetric varieties of DSL, and subsequent sections deal with the asymmetric variations.[2]

5.4.3 Basic Rate ISDN (BRI)

Basic rate integrated services digital network (ISDN) is regarded by many as the "original" DSL [Starr 1999]. ISDN was intended to provide a global digital network for the integrated transmission of voice and data signals. The focus in ISDN was on transmission of voice signals, and low-speed data signals. Basic rate ISDN (BRI) is capable of transmitting up to

[2] As noted previously, some of the "asymmetric" technologies can also be used for transmission of symmetric bit rates.

160 kbit/s, symmetrically, over distances of approximately 5.5 km (18,000 ft) on a single span. Operation over longer distances is possible with the use of repeaters. The transmission bit rate is divided into two "B" channels, each carrying 64 kbit/s, and one "D" (Data) channel carrying 16 kbit/s. The remaining 16 kbit/s are used for framing and control. The majority of installed ISDN uses 2-binary, 1-quaternary (2B1Q) PAM (see Section 4.5.1) at a symbol rate of 80 kHz. Bidirectional transmission in the same bandwidth is achieved by the use of echo cancellation.

Further details on ISDN may be found in [Starr 1999], [ANSI T1.601 1992], [ETS 300 403], [Stokesberry 1993], and [IEEE Com. Mag. Aug. 1992].

5.4.4 HDSL

High-bitrate digital subscriber line (HDSL) is the term that is usually applied to the provision of symmetric T1 (1.544 Mbit/s) or E1 (2.048 Mbit/s) rates over one, two, or three copper twisted pairs. Development and deployment of HDSL technology started in the late 1980s and early 1990s, and it is now widely used throughout the developed world, especially in North America. One of the motivations for the development of this technology arose from the increased usage of T1 and E1 transmission to customer premises; the traditional technology used for this purpose (based on alternate mark inversion (AMI) and high-density bipolar 3 (HDB3) modulation) was problematic from the point of view of plant engineering (requiring loop qualification) and crosstalk generation. HDSL alleviated many of these problems. Most deployed HDSL uses similar technology to BRI, *i.e.*, 2B1Q modulation, plus echo cancellation. However, European specifications also include provision for the use of single-carrier modulation, in particular, carrierless amplitude/phase (CAP) modulation (see Section 6.2.3).

The most commonly deployed variant of HDSL uses two twisted pairs, whereby half of the transmitted data is sent (in both directions) on each. For example, transmission of 1.544 Mbit/s is accomplished by transmitting half of the data (784 kbit/s including overhead) over each twisted pair. Furthermore, the use of "one pair" of two-pair HDSL to provide fractional-rate T1 or E1 bit rates (*i.e.*, half of the full rate) is quite common. This type of service would be used, for example, to serve "small" business customer sites where the volume of traffic does not justify the cost of a full T1 or E1 link. In Europe, HDSL is also specified for operation over a single pair carrying 2.320 Mbit/s; two pairs, each carrying 1.168 Mbit/s; and three pairs, each carrying 784 kbit/s. More information on HDSL as used in North America may be found in [ANSI T1 1994], and details on the European specification may be found in [TS 101 135 2000].

An interesting extension of HDSL technology was the development of DSL systems that transmitted data at rates of $n \times 8$ kbit/s, where n is an integer. These systems were based on both 2B1Q and also CAP technology and, though official recommendations were never actually produced, this technology has been widely deployed, largely by competitive local exchange carriers. These systems are often referred to as symmetric digital subscriber line (SDSL), which is not to be confused with ETSI's SDSL specification (described in Section 5.4.6).

Two-pair HDSL can operate over a single span of up to 3.7 km (12,000 ft) of 0.5 mm wire; however, its range can be greatly extended with the use of repeaters. The use of more than one pair helps to ensure longer reach, because the bandwidth used on each pair is less than would be used with a single pair, and hence the attenuation suffered by the signal per km of reach is also less. Lower bandwidth also helps to facilitate spectral compatibility with existing systems. However, the use of more than one pair per customer means that fewer customers can be served with a given number of twisted pairs; single-pair systems have the advantage that more customers can be served. The late 1990s saw the development of a high-performance replacement for HDSL, which would use a single pair, but would be spectrally compatible with existing systems. This technology is described in the next subsection.

5.4.5 HDSL2 and HDSL4

As noted above, there was a strong requirement for a technology to replace "HDSL-like" systems, utilizing a single twisted copper pair and providing high performance (adequate reach) while retaining spectral compatibility with other services. This led to the development within T1E1.4 of "second generation HDSL," or so-called "HDSL2." Like HDSL, the technology for HDSL2 is based on echo-cancelled PAM, but HDSL2 incorporates many innovations that were not present in HDSL. Among these is the use of error-correcting codes to enhance performance. HDSL2 uses powerful trellis-coded modulation (TCM), which is discussed in more detail in Chapter 8. The use of TCM can provide several dB of extra performance (in the form of coding gain) to the system. This was found to be particularly important for HDSL2, given the ambitious performance targets (essentially doing the same thing as HDSL, but with only one twisted pair). The HDSL2 standard is flexible enough to allow vendors to choose the parameters of the system (including a programmable convolutional code) to give just the required amount of coding gain, and hence trade-off complexity in the TCM decoder against performance. However, the standard includes an example of a code that provides up to 5 dB of gain. HDSL2 uses coded 16-PAM modulation with three information bits and one redundant bit per symbol, resulting in a symbol rate of 517.33 kHz for transmission of T1 rates (including HDSL2 overhead). Because of the presence of TCM, HDSL2 requires the use of precoding [Tomlinson 1971] [Harashima 1972], whereby some of the equalization normally carried out by a traditional equalizer in the receiver (see Chapters 6 and 11) is instead carried out by the transmitter (*i.e.*, the signal is pre-equalized before transmission).

A further innovation is the use of asymmetric spectra for the signals in the upstream and downstream directions. Unlike 2B1Q HDSL, where the shape of the transmit signal spectrum is the same in both directions of transmission, the HDSL2 transmit signal has two different (overlapping) shapes for the two directions of transmission. (Note that this type of asymmetry should not be confused with asymmetry in the transmitted bit rate.) Among the reasons for this were the need to reduce the effect of self-crosstalk (and thus ensure that the performance requirements would be met), and also to enhance spectral compatibility.

The general performance requirements for HDSL2 are outlined in [ANSI T1 2000]; in essence, the service is expected to operate in the presence of a number of different types of disturber, over a particular set of test loops conforming to carrier serving area (CSA) design rules (in simple terms, up to 2.7 km (9,000 ft) of 0.4 mm wire, or 3.7 km (12,000 ft) of 0.5 mm wire). Operation over longer loops is possible through the use of repeaters; however, the use of repeaters has implications for spectral compatibility with other services.

To allow for the provision of T1 service over loops beyond carrier service area (CSA) limits while retaining spectral compatibility, T1E1.4 developed a two-pair version of HDSL2, which is commonly referred to as "HDSL4."[3] As with two-pair HDSL, half of the transmitted data is carried on each of the two pairs. The fact that the bit rate on each pair is lower means that less bandwidth is required, which in turn means that the signal on each pair suffers less attenuation and hence longer reach can be achieved (around 3.4 km of 0.4 mm wire). HDSL4 uses largely the same technology as HDSL2, *i.e.*, coded 16-PAM modulation with

[3] There is an ironic closing of the circle in this development, in the sense that HDSL2 was a single-pair version of the multi-pair HDSL, whereas HDSL4 is a multi-pair version of HDSL2.

asymmetric upstream and downstream spectra. However, the spectra for HDSL4 are quite different from those for HDSL2.

5.4.6 SDSL

In Section 5.4.4, reference was made to "SDSL" based on 2B1Q technology, essentially a single-pair version of HDSL capable of operation at a number of different bit rates. In the late 1990s, ETSI TM6 started work on a symmetric multi-rate technology that supports mainly business customers with bit rates of $n \times 64$ kbit/s, up to a maximum of 2.304 Mbit/s ($n = 36$), plus overhead. The bit rate provided is a function of the loop length over which service is provided: the shorter the loop, the greater the bit rate that can be delivered. This technology is referred to as symmetrical single-pair high-bitrate digital subscriber line, using the same acronym "SDSL."

In some ways, ETSI SDSL is similar to 2B1Q SDSL referred to earlier (symmetric bit rate, multi-rate operation). However, ETSI SDSL also has much in common with HDSL2 and HDSL4 in that it makes use of TCM and transmits three information bits per symbol, as opposed to two bits per symbol with 2B1Q. Also, although the transmit spectra in ETSI SDSL are symmetric, some provision is made for asymmetric spectra at the highest bit rates (2.048 and 2.304 Mbit/s) in order to enhance performance and increase spectral compatibility. Further details on ETSI SDSL may be found in [TS 101 524 2001].

5.4.7 G.shdsl

Thus far, the discussion has covered a number of symmetric bit rate technologies: basic rate ISDN, HDSL, 2B1Q SDSL, HDSL2, HDSL4, and "ETSI SDSL." Development of these individual technologies has generally taken place under the auspices of regional standards bodies such as T1E1.4 and ETSI TM6. However, the ITU-T has also been quite active in DSL standards development through its Study Group 15/Question 4 working group. For example, ITU-T has published Recommendation G.991.1, covering HDSL technology. In addition, it has developed recommendations for symmetric bit rate, multi-rate DSL technology that draws heavily on the developments in the regional standards bodies. In ITU-T parlance, this is referred to as single-pair high-speed digital subscriber line, with the acronym SHDSL; the relevant recommendation is G.991.2, also commonly known as G.shdsl [ITU-T G.991.2 2001].

G.shdsl defines operation at payload bit rates from 192 kbit/s up to 2.304 Mbit/s, in increments of 8 kbit/s, over a single wire pair (though there is an optional two-pair mode that can be used for greater reach). It includes many of the features of HDSL2/4 and ETSI SDSL, including symmetric bit rates, multi-rate operation, and the use of 16-level trellis-coded (TC) PAM. Many of the operational elements of G.shdsl are region-specific, and the ITU-T recommendation includes a number of annexes that contain details specific to a particular geographical region. For example, Annex A contains information that is specific to North America, and Annex B contains details of how G.shdsl systems would be deployed in Europe. The technical content of these annexes has largely originated in the respective regional standards bodies (*i.e.*, ANSI T1E1.4 and ETSI TM6), so in a sense, G.shdsl encompasses a number of the DSL technologies discussed above, in particular, HDSL2, HDSL4, and SDSL.

G.shdsl systems have a two-phase start-up sequence: pre-activation and core activation. The purpose of the pre-activation phase is to allow the transceivers on either end of the line to exchange information about their capabilities and to agree upon the best configuration given the loop and noise conditions. This is necessary because the G.shdsl recommendation covers many possible configurations, both mandatory and optional, so it is important that

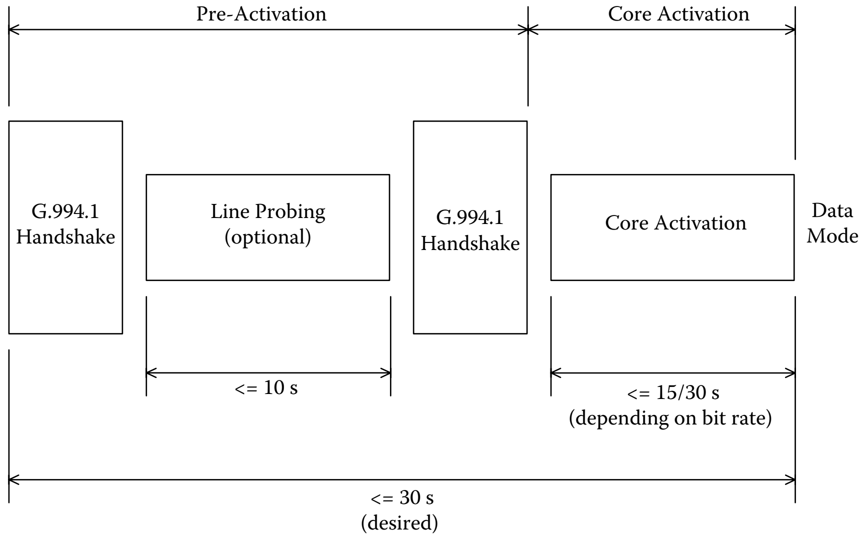

FIGURE 5.4
Timeline of G.shdsl activation sequence.

the transceiver on one end of the loop know the capabilities of the other one. Once this exchange has taken place, the core activation takes place, whereby the receiver (and transmitter) functional blocks are adapted so that reliable communication at the agreed-upon bit rate can take place. The pre-activation sequence also includes an optional line probe during which each transceiver may examine the loop and noise conditions and determine (for example, through SNR measurements) the bit rates it is capable of supporting under these conditions. Figure 5.4 shows the timeline of the entire G.shdsl activation sequence; the handshake portions are where the two transceivers exchange information about their respective capabilities, and the optional line probe portion is where particular signals are transmitted from one transceiver to the other, in order that information about the operating conditions may be obtained. ITU-T Recommendation G.994.1 [ITU-T G.994.1 2003], commonly known as "G.hs," describes the manner in which the handshaking takes place.

Since the initial publication of the G.shdsl recommendation, further developments have taken place in the various standards committees that have resulted in enhancements to the basic specification. For example [ITU-T PF-R15 2003]:

- Two-pair operation has been extended to multi-pair operation.
- Optional provision has been made to allow for transmission of bit rates up to 5.696 Mbit/s.
- The capability to carry out a shorter-duration "warm-start" has been added.
- Support for transport of packet-mode data has been included.

5.4.8 ADSL

The discussion thus far has concentrated mainly on the varieties of DSL that transmit symmetric bit rates (both single-rate like HDSL2 and multi-rate like G.shdsl). For the most part, such systems are of most benefit to business customers. Of perhaps greater demographic importance are the DSL technologies that support asymmetric bit rates, which more closely match the requirements of most residential customers (for Web browsing, etc.).

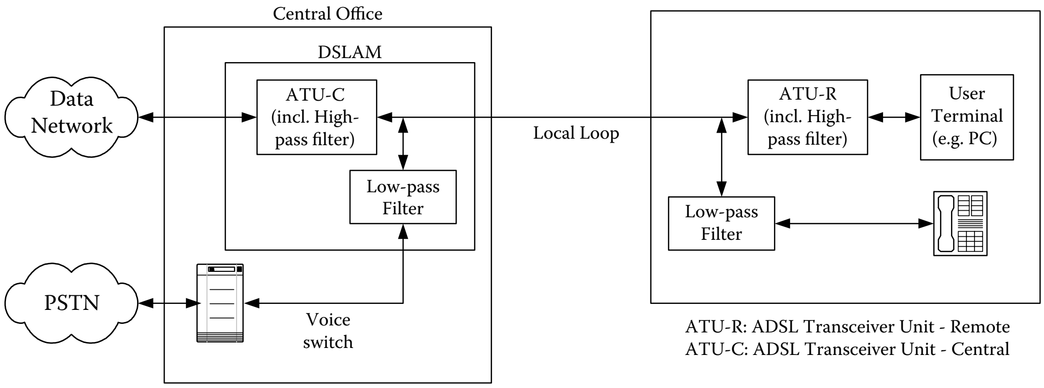

FIGURE 5.5
Block diagram of ADSL reference model.

The most widely deployed form of this technology is the original definition of asymmetric digital subscriber line (ADSL), which is capable of providing data rates of up to 8 Mbit/s downstream (*i.e.*, toward the consumer) and up to 896 kbit/s in the upstream direction. Transmission uses one pair of wires. The original motivation for the development of this technology was video on demand; however, the commercial motivation for ADSL quickly changed to high-speed Internet access in the mid-1990s.

As noted above, most of the asymmetric DSLs make use of modulation that avoids the lowest few kHz of the available spectrum on the loop. This is to ensure that lifeline POTS can still function, whether or not the DSL service is operational. The spectrum of the ADSL signal starts around 25 kHz. To separate the two services (ADSL and POTS), a pair of low-pass and high-pass "splitter" filters is required (see the splitter chapter in Volume 2 for more details on splitters and related technology). A block diagram of a typical ADSL reference model is shown in Figure 5.5. A variation of this basic configuration permits the operation of an ADSL system above ISDN, which has a substantially higher bandwidth than POTS (80 or 120 kHz, depending on the modulation used for ISDN). This is of particular interest in some European markets where ISDN is widely deployed.

As with symmetric DSL, ADSL technology has been standardized by the various regional and global standardization bodies; both DMT and single-carrier technologies were originally proposed for ADSL, though the standards are based on DMT modulation. The North American recommendation can be found in [ANSI T1 1998], and the European recommendation developed by ETSI TM6 is in [TS 101 388 2002]. Furthermore, ITU-T has also created Recommendation G.992.1 ("G.dmt") [ITU-T G.991.1 1999] to cover this type of "full-rate" ADSL, incorporating many of the features of the regional standards.

Like the more advanced symmetric DSLs, ADSL makes use of techniques such as error-correcting codes (see Chapter 9), as well as various techniques for choosing the optimum bit rate for the line conditions (in much the same way as G.shdsl uses line probing). For example, ADSL uses variable constellation sizes and sophisticated bit allocation algorithms to determine where best to distribute energy in the usable bandwidth (see Chapter 7).

Because the upstream rate in ADSL is much lower than the downstream rate, it follows that the bandwidth required for upstream transmission is much less than that required for downstream transmission. Upstream transmission generally uses the frequency range from around 25 kHz to around 138 kHz for transmission. Downstream transmission may occur in either of two bands, depending on the mode of operation of the ADSL transceiver. Full overlap between the downstream and upstream bands may be utilized, in which case downstream transmission uses the band from 25 kHz to around 1.104 MHz.

This results in more available bandwidth for downstream transmission, which may increase transmission rate. Sophisticated echo cancellation techniques are needed in this case, and crosstalk into the upstream channel is increased. A much more commonly used mode of operation is frequency division duplexing (FDD), where the downstream and upstream bands do not overlap. In this case, downstream transmission starts at around 138 kHz.

5.4.9 Splitterless ADSL

Besides the "full rate" ADSL described in the previous subsection, a simpler variant that does not require a splitter has also been developed. One of the motivations for this was to enable easier installation of ADSL at the customer's premises, in particular, to avoid installation of the splitter and (possibly) new premise's wiring. However, removal of the filters means that interference from the POTS service can leak into the ADSL transmission and vice versa. Therefore, it is necessary to use a so-called "in-line" low-pass filter in series with each telephone in the user premises to reduce these effects; these filters are available in modular form for easy installation by the customer. This type of installation of ADSL is referred to as "splitterless," even though in-line filters are required. The ITU Recommendation G.992.2 ("G.lite") was written to specify splitterless ADSL, and it places restrictions on the data rate to ensure reliable performance: the downstream data rate is limited to 1.5 Mbit/s. However, experience has shown that "splitterless" full-rate ADSL is achievable using in-line filters, and this installation mode is now common for ADSL [ITU-T G.992.3 2002]. As a consequence, G.lite never really gained traction in the marketplace.

5.4.10 ADSL2, ADSL2plus

Since the development of the original ADSL specification, a number of enhancements have been made in order to increase performance (in terms of higher bit rate, increased reach, and better management and diagnostic control). As before, many of the developments have been driven by the work of regional standards bodies, and these enhancements to the original G.992.1 have been captured by ITU-T as G.992.3, also known as "ADSL2" [ITU-T G.992.3 2002]. The enhancements (many of which are optional) include:

- The addition of a single-bit constellation for more robust performance over longer loops (thus enabling operation over loops that were previously unusable), and the inclusion of mandatory trellis coding (previously optional).
- The inclusion of "seamless" rate adaptation to enable almost continuous changes to the bit rate, and the distribution of bits across the used bandwidth (online "bit swapping").
- Changes to the error-correction coding (including greater flexibility).
- Inclusion of an optional "all digital" mode that allows the use of the POTS band for transmission of additional data by the ADSL modem.
- Several features to combat interference (including RFI).
- Improved initialization procedures, and an optional "fast" initialization mode (around 3 s).
- Flexibility in the amount of ADSL overhead that is used (allowing more bits/s for user data), and more comprehensive diagnostic features.
- Supports for bonding several ADSL channels together, as well as support for transport of packet-based services such as Ethernet.

An additional specification based on ADSL2, called "ADSL2plus," has also been written. The main additions in ADSL2plus are:

- Extension of the upper limit of the downstream bandwidth from the original 1.1 MHz to 2.2 MHz. This results in higher downstream bit rates on short-to-medium length loops.
- Spectral shaping of the downstream transmit PSD, to allow greater flexibility in configuration for particular conditions (for example, to meet regional requirements and to improve the spectral compatibility of CO and remote deployments).

5.4.11 VDSL

Very-high bit rate DSL (VDSL) is currently the highest-speed DSL variant, which provides tens of Mbit/s to users in order to extend the performance of existing applications in Internet access, video-conferencing, provision of digital video, telemedicine, and distance learning. In a sense, VDSL is an extension of existing ADSL technology; however, provision of higher bit rates can only be carried out over shorter loops. In fact, the deployment architecture for VDSL is quite similar to the hybrid fiber-coax network described earlier; *i.e.*, fiber-optic transmission is used to connect the central office with a remote optical network unit (ONU), which may be located, for example, at the end of a street. The remaining (short) distance between the ONU and the customer premises is covered using VDSL transmission over the usual twisted copper pair. This architecture could be referred to as hybrid fiber–copper.

VDSL can support both symmetric and asymmetric bit rates. In particular, first-generation VDSL (known as VDSL1) can support 13 or 26 Mbit/s symmetrically, whereas asymmetric transmission can provide up to 52 Mbit/s downstream with 6.4 Mbit/s upstream. The highest downstream rates can only be achieved over short loops. To achieve high bit rates, VDSL uses up to 12 MHz of bandwidth (as opposed to the 1.1 or 2.2 MHz used by ADSL and ADSL2plus, respectively). In one sense, VDSL may be suitable for both broad categories of application, *i.e.*, "residential" applications (largely asymmetric-rate) and "business" (largely symmetric-rate). Like ADSL, VDSL is also capable of operating in the presence of existing POTS or ISDN transmission, using the same "splitter" concept. Although theoretically VDSL could operate using either FDD (no overlap between downstream and upstream transmission) or echo-cancellation (some overlap between downstream and upstream), practical echo-cancelled operation would be extremely difficult to achieve due to the high bandwidths, so VDSL development has largely concentrated on the use of FDD.

From the perspective of standards development, both regional standards bodies and the ITU-T have active projects in this area. In particular, these standards bodies have defined a number of PSD masks for use with VDSL, including the use of multiple disjoint frequency bands for upstream and downstream transmission. Both DMT and QAM/CAP technologies are used in VDSL1, whereas second-generation VDSL (VDSL2) specifies only DMT for the physical layer. Further details on VDSL standards may be found in Volume 2 of this series, and additional information on VDSL technology may be found in [Cioffi 1999] and [IEEE Com. Mag. May 2000].

5.4.12 Related Topics

5.4.12.1 Spectrum Management

Previous chapters have covered the impact of crosstalk on the performance of a DSL system. Clearly, one type of DSL may interfere with another type. Apart from the fundamental performance requirements of DSL systems, an additional requirement is that new types of DSL systems should be spectrally compatible with existing (legacy) systems; that is, they should not cause any undue degradation in the performance of these legacy systems [Starr 2003]. Typically, limits are placed on the PSDs of the transmit signals of new services in order to ensure spectral compatibility. In addition, rules or guidelines exist as to how different types of DSLs may be deployed, particularly in nonhomogeneous situations. For example, where different DSLs with very different PSDs are present in the same binder cable, care must be taken to ensure that all services have acceptable performance. These guidelines constitute what is generally called spectrum management. For example, [ANSI T1 2001] specifies spectral compatibility requirements for North America. This includes a list of legacy systems with which new technologies must be compatible, as well as methods for determining if this compatibility exists, and spectrum management deployment rules. Spectrum management (and related topics) is described in more detail in Volume 2 of this series.

A recent development in DSL technology is dynamic spectrum management (DSM). This has arisen from the recognition that the existing fixed spectrum management guidelines are predicated on DSL systems operating in worst-case conditions. However, DSL systems may well operate in more benign conditions most of the time. DSM attempts to allow DSL systems to achieve the maximum possible performance, while remaining spectrally compatible. In particular, instead of treating each DSL line in isolation, DSM looks at all of the lines in a given binder cable as a multi-user system and performs joint optimization to ensure maximum performance of all systems. Dynamic spectrum management and related issues are covered in detail in Volume 2 of this series and are also described in [Song 2002].

5.4.12.2 Deployment and Testing

As with any communications system, testing and related deployment issues are extremely important; these topics are covered in depth in Volume 2 of this series, which includes chapters on wire line channel simulation, evolution of test procedures from POTS to DSL, and loop qualification and planning for DSL deployment.

5.4.12.3 End-to-End Architectures

This chapter has largely focused on the physical layer of DSL systems, but clearly DSL is of no benefit unless it carries useful services. A large number of different types of service may be carried over DSL, including synchronous data, ATM data, and packet-based services. Figure 5.3 suggested that the physical part of the DSL largely exists on the local loop between the user and the nearest central office. However, from the service perspective, the situation is much broader. The chapters in Volume 2 of this series will address how the DSL physical layer may be used as part of end-to-end system architectures, for example, how DSL may be used to carry services such as packet-based data, and also voice services (so-called voice over DSL, or VoDSL). Volume 2 will also cover topics such as how the flexibility that exists in DSL systems may be leveraged to provide service differentiation, as well as issues in DSL operations and maintenance and security.

5.4.12.4 Ethernet in the First Mile (EFM)

Recent work in IEEE Task Force 802.3ah is aimed at the provision of "full" Ethernet services all the way to a customer premises; this concept is referred to as "Ethernet in the first mile" (EFM). Although copper-based Ethernet standards currently exist for the provision of bit rates up to 1 Gbit/s, there are restrictions on the length and quality of line that may be supported. For example, at higher speeds, Ethernet typically requires multiple pairs of wires of a certain minimum quality.

There is some interest in the use of DSL as a potentially ideal physical layer for the provision of EFM services over copper. In particular, IEEE 802.3ah has standardized VDSL as the transmission technology for use over short loops ($\geq$10 Mbit/s symmetric over 750 m), and G.shdsl has been selected for transmission over longer distances ($\geq$2 Mbit/s over loops of length 2.7 km); the latter is of particular interest in North America, where the average loop length tends to be longer.

Further information on this project may be found in [IEEE 802.3ah].

5.5 Representative DSL Transceivers

The previous section gave a broad overview of the different classes of DSL technology and briefly covered their salient features. This section attempts to dig more deeply into how DSL systems are actually realized, as a prelude to later chapters that describe the different technologies in more detail (both from the point of view of the fundamental underlying algorithms, as well as implementation-related issues). Design of DSL physical layers encompasses many different technologies, particularly digital signal processing (DSP), advanced coding techniques for error correction, and high-performance analog technology.

Functional block diagrams of “typical” DSL systems are introduced, and the various blocks described in later chapters are highlighted. DSL systems use one of three basic modulation techniques: PAM, QAM/CAP, or DMT. Each modulation type has its own unique characteristics; at the same time, there is some commonality in functional blocks between DSL systems, particularly in functions like error correction. Therefore, in the interests of simplicity, “representative” systems for each modulation method will be presented, and each of these systems will be deemed to be representative of all of the DSLs that use this modulation. For example, PAM is used in HDSL, HDSL2, HDSL4, and G.shdsl. This is clearly a gross simplification, because many differences exist even between systems that use the same basic modulation technique; however, it will suffice for the purposes of this chapter.[4] Later chapters will deal with each transceiver function in more detail and will also point out the differences between the multiple systems that use the same basic modulation technique.

5.5.1 Symmetric DSLs

A block diagram of a DSL transceiver to provide symmetric bit rates using PAM is shown in Figure 5.6. Although this particular block diagram is closest to a G.shdsl transceiver, the basic functions are also common to other symmetric DSLs. The major functional blocks are described in the following subsections.

5.5.1.1 Scrambler and Descrambler

The function of the scrambler is to randomize the transmit data bits that are provided to the DSL transceiver. This is necessary in order to ensure optimum performance of several transceiver components, for example, the equalizer and the echo canceller. At the receiver side, the descrambler carries out the inverse operation of the scrambler in order to regenerate the payload data.

5.5.1.2 Trellis-Coded Modulation (Encoder and Decoder)

Trellis-coded modulation is used in many systems to provide increased robustness to errors, and hence increase the achievable bit rate or reach. The basic principle of this technique

[4] Also, it is important to point out that the block diagrams as presented here are simply examples used for illustrative purposes; real systems may differ in some respects.

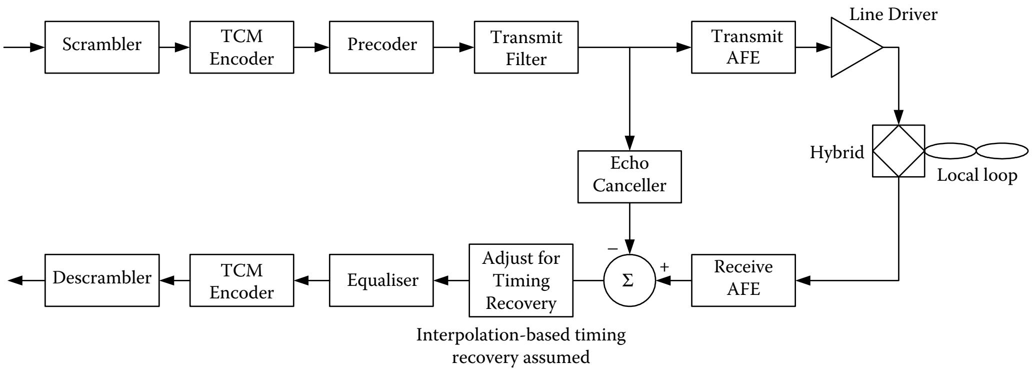

FIGURE 5.6
Block diagram of a "generic" symmetric DSL transceiver (baseband).

is to add redundancy to the transmitted data in order to enable the receiver to correct errors. The TCM decoder is typically implemented using the Viterbi algorithm, though other possibilities exist. Trellis coding is described in more detail in Chapter 8. HDSL2, HDSL4, and G.shdsl make use of TCM; HDSL does not.

5.5.1.3 Equalizer and Precoder

Equalization is required in DSL receivers in order to ensure reliable performance in the presence of channel distortion and interference (crosstalk, background noise, etc.). Effectively, equalization attempts to compensate for these noises and distortion; put simply, it "cancels out" signal distortion. When used with TCM, equalization is most often implemented with the aid of a precoder in the transmitter. In essence, part of the equalization function that would normally be carried out at the receiver is instead transferred to the transmitter; *i.e.*, the transmit signal is "pre-equalized" before it is sent through the channel. Obviously the transmitter needs to have some knowledge of the equalization that is required, and this information is usually transferred from receiver to transmitter as part of the transceiver startup procedure. Equalization is described in detail in Chapter 11.

5.5.1.4 Transmit Filter

Each DSL standard has particular limitations on the PSD of the transmitted signal, which implies that the transmit signal must somehow be "shaped" so that it conforms to this PSD specification. This shaping is typically carried out in the transmit filter (which is also commonly referred to as a "spectral shaper"). For example, for HDSL2 or HDSL4, the transmit filter needs to be able to impose quite complex PSDs on the transmit signal, with different PSDs required for the upstream and downstream directions.

5.5.1.5 Transmit Analog Front End (AFE)

The transmit AFE provides the interface between the DSL "datapump" (which is generally implemented using DSP technology) and the analog transmission medium. In particular, this function will encompass digital-to-analog conversion, analog filtering, and line driver functionality to ensure sufficient signal power is supplied to the line. This circuit interfaces with the hybrid circuit, which connects the four-wire circuit of the DSL transmitter and receiver to the two-wire subscriber line.

5.5.1.6 Receive AFE

The receive AFE provides similar functionality to the transmit AFE, but in the opposite direction. Indeed, both functions would normally be implemented in the same physical piece of hardware, but they are treated here as different entities for clarity. The receive AFE would normally include analog filtering to limit noise and minimize aliasing, and an analog-to-digital converter (ADC). Normally, this circuit would also include an analog automatic gain control (AGC) circuit to optimize the signal level for the ADC input.

5.5.1.7 Echo Canceller

Most of the symmetric bit rate DSLs overlap the downstream and upstream signals in frequency. Because of the imperfect nature of the hybrid interface, impedance mismatches exist, resulting in a significant echo of the transmit signal being received by the near-end receiver. This is essentially a source of interference to the received signal, albeit one for which the interference source is known. The hybrid circuit itself tries to reduce the amount of echo that is received; however, this is usually insufficient, and an adaptive echo canceller must be employed to ensure that the received echo does not dominate the noise in the received signal.

5.5.1.8 Timing Recovery

Because a DSL transmitter and receiver for a given transmission direction are located at opposite ends of a subscriber loop, there will naturally be differences in the frequencies of the symbol (and other) clocks between transmitter and receiver, which is a significant source of error if not corrected. Correction of these differences is the function of the timing recovery (or synchronization) block. In essence, this function tries to regenerate the clock that would be used in the transmitter and hence generate the data that would have been sent from the transmitter. There are many different techniques for timing recovery; some techniques attempt to vary the clock used to control the time instants at which the ADC actually samples the data, whereas others do not modify the ADC sampling clock, but instead attempt to carry out "all digital" timing recovery, *e.g.*, using signal interpolation. Techniques for synchronization are described in Chapter 12.

5.5.1.9 Additional Functions

The previous discussion has identified the key functional blocks of symmetric-rate DSL transceivers, most of which are described in more detail in subsequent chapters. However, there are many other functions that have not been covered in this section. For example, transceivers must implement functions to control the startup or initialization procedure when a connection is established between two DSL modems. Furthermore, many DSL technologies are multi-rate, which means that many parameters of the functional blocks must be properly configured (for example, different symbol clocks may be used for different bit rates, different PSDs may need to be imposed by the transmit filter, etc.). Although the various standards specify many details of functions such as these (for example, the procedures to be used for startup), the details of implementation of these functions are very much vendor-specific.

5.5.2 Passband Single-Carrier Systems

A block diagram of a typical DSL system using passband single-carrier modulation (QAM/CAP) is shown in Figure 5.7. This could be representative of a transceiver used for VDSL1 (though CAP has also been specified for use in providing HDSL service in Europe).

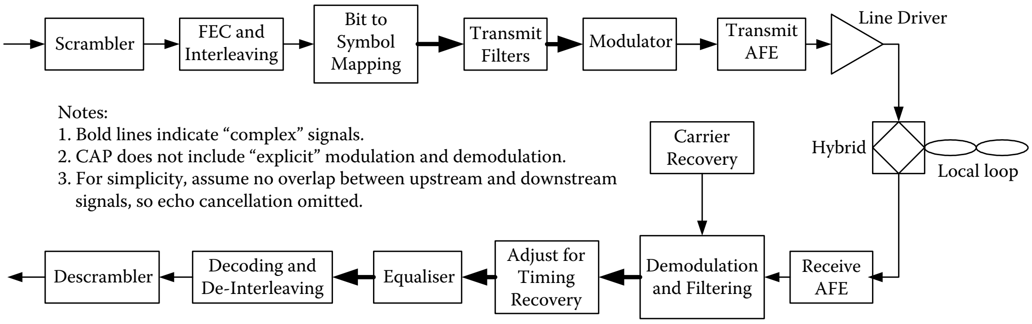

FIGURE 5.7
Block diagram of a generic passband single-carrier DSL transceiver (QAM/CAP).

Many of the blocks used in CAP/QAM systems have similar functions to those used in PAM systems (although many of the details are different), so this subsection will only focus on those functions where significant differences exist. One point to note is that in CAP/QAM systems, the datapath consists of in-phase and quadrature (real and imaginary) components, so most of the filters (equalizer, etc.) can be viewed as processing signals in the form of complex numbers.

5.5.2.1 Error Correction and Interleaving

Only TCM is used in most symmetric rate DSL systems. With other systems such as VDSL1, additional methods for mitigating errors are used. In particular, such systems make use of Reed–Solomon coding and interleaving (see Chapter 9).

5.5.2.2 Modulation and Demodulation

Unlike baseband PAM systems, CAP/QAM systems "shift" the transmit signal frequency up to some defined frequency, depending on the particular DSL service being provided. Hence, CAP/QAM systems use some form of modulation to shift the spectrum. In the case of QAM, this generally takes the form of multiplication of the baseband signal (in complex form) by in-phase and quadrature (cosine and sine) carriers. At the receiver, another multiplication by the carriers must be carried out, in order to shift the signal back down to baseband again.

In the case of CAP modulation, there is no "explicit" multiplication by carriers; instead, the modulation is "implicit" in the impulse responses of the transmit filters, thus avoiding the need for additional carrier generation. Many systems can operate in "dual-mode"; *i.e.*, they can transmit and receive both QAM and CAP signals.

5.5.2.3 Carrier Recovery

For effective demodulation and recovery of the transmitted data, it is important that the frequency and phase of the demodulator carrier in the receiver match those of the carrier used in the transmitter. Because there will always be some inherent difference between the two carriers (for the same reasons that there are differences in the symbol clock frequencies, as discussed above), it is necessary for the receiver to attempt to "recover" the characteristics of the carrier used in the transmitter; this is normally carried out by the carrier recovery block (the function of carrier recovery is similar in many ways to the function of timing recovery discussed earlier).

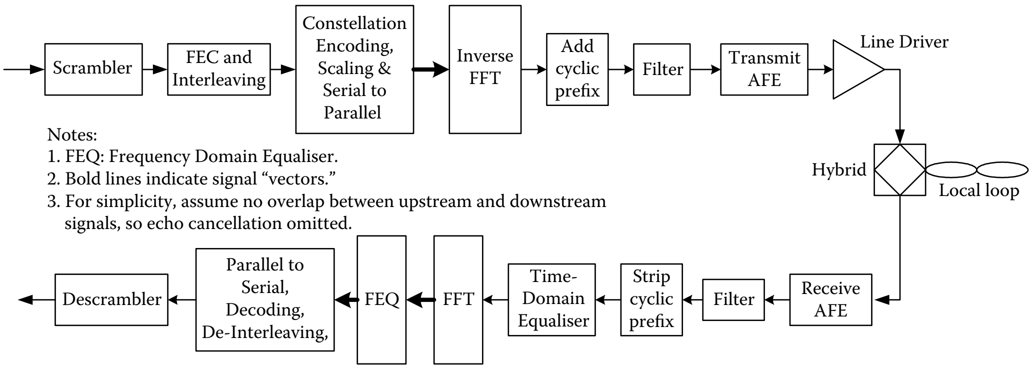

FIGURE 5.8
Block diagram of "generic" DMT-based DSL transceiver (multi-carrier).

5.5.2.4 Additional Points

Although QAM and CAP technology have been classified here as passband single-carrier systems, it should be pointed out that in some DSL systems, QAM and CAP technology may actually make use of multiple carriers. For example, VDSL1 systems may use two disjoint frequency bands for each direction of transmission, with each band utilizing a separate carrier. So, although such systems could be viewed as multi-carrier, it is more commonly the case that these systems are referred to as multi-band single carrier.

Single-carrier modulation is described in detail in Chapter 6.

5.5.3 Multi-Carrier Systems

The third principal type of modulation that is widely used in DSL systems is multi-carrier modulation, specifically, discrete multi-tone (DMT) modulation. A block diagram of a generic DMT-based transceiver is shown in Figure 5.8.

Many of the blocks have the same function as for PAM and CAP/QAM systems; however, a significant difference lies in the modulation. In simple terms, the transmitted data stream is divided among a large number of subcarriers, with the system as a whole operating at a low symbol rate.[5] In the case of DMT however, modulation and demodulation are carried out using Fourier transform, resulting in orthogonal carriers. Furthermore, DMT systems generally use carriers that are reasonably closely spaced, which implies that the magnitude response of the channel is almost "flat" across the bandwidth of each carrier; this means that equalization may be simplified. Chapter 7 describes multi-carrier modulation and DMT in detail.

5.5.4 Closing Remarks

This subsection has introduced representative block diagrams of various types of DSL systems, identifying the major functional blocks that are used, and also pointing out major similarities and differences between different classes of systems. Although the discussion has focused on the functionality, implementation is clearly an important aspect of DSL systems development as well. Chapters in Volume 2 of this series address a number of implementation aspects.

[5] In one sense, this is like a multi-band single-carrier system, though with many more carriers than would normally be the case.

5.6 Summary

This chapter has briefly discussed some of the motivations for the development of DSL systems, including the benefits and disadvantages of alternative local access mechanisms that may be used. It then continued to describe the principal DSL systems that are in use or under development, many of the details of which are described in later chapters. Finally, representative block diagrams of the main classes of DSL transceiver were presented, in order to highlight the most important functional blocks that form part of a typical DSL transceiver.

Later chapters will describe DSL technology in greater detail, both from the point of view of the fundamental technologies used in these systems, as well as in the specifics of particular DSL standards.

References

[ANSI T1.601 1992] ANSI T1.601. *ISDN Basic Access Interface for Use on Metallic Loops for Application on the Network Side of the NT (Layer 1 Specification).* 1992.

[ANSI T1 1994] ANSI Committee T1. *High Bit-Rate Digital Subscriber Line (HDSL) Technical Report.* 1994.

[ANSI T1 1998] ANSI Committee T1. *Asymmetric Digital Subscriber Lines Metallic Interface.* Issue 2, T1.413-1998.

[ANSI T1 2000] ANSI Committee T1. *High Bit-Rate Digital Subscriber Line — 2^{nd} Generation.* T1.418-2000.

[ANSI T1 2001] ANSI Committee T1. *Spectrum Management for Loop Transmission Systems.* T1.417-2001.

[Ayanoglu 1998] E. Ayanoglu, N.R. Dagdeviren, G.D. Golden, and J.E. Mazo. *An Equalizer Design Technique for the PCM Modem: A New Modem for the Digital Public Switched Network.* IEEE Trans. on Communications, 46(6), pp. 763–774, June 1998.

[Boelcskei 2001] H. Boelcskei, A.J. Paulraj, K.V.S. Harhi, R.U. Nabar, and W.L. Lu. *Fixed Broadband Wireless Access: State of the Art, Challenges and future Directions.* IEEE Communications Magazine, 39(1), pp. 100–108, January 2001.

[Cioffi 1999] J.M. Cioffi, V. Oksman, J.-J. Werner, T. Pollet, P.M.P. Spruyt, J.S. Chow, and K.S. Jacobsen. *Very-High-Speed Digital Subscriber Line.* IEEE Communications Magazine, 37(4), pp. 72–79, April 1999.

[Cramer 2002] G. Cramer and G. Pesavento. *Ethernet Passive Optical Network (EPON): Building a Next-Generation Optical Access Network.* IEEE Communications Magazine, 40(2), pp. 66–73, February 2002.

[ETS 300 403] ETSI Specification ETS 300 403. *Integrated Services Digital Network.*

[Forney 1984] G.D. Forney, R.G. Gallager, G.R. Lang, F.M. Longstaff, and S.U. Qureshi. *Efficient Modulation for Band-Limited Channels.* IEEE Journal on Selected Areas in Communications, 2(5), pp. 632–647, September 1984.

[Forney 1996] G.D. Forney, L. Brown, V. Eyuboglu, and J.L. Moran. *The V.34 High-Speed Modem Standard.* IEEE Communications Magazine, 34(12), pp. 28–33, December 1996.

[Harashima 1972] H. Harashima and H. Miyakawa. *Matched Transmission Technique for Channels with Intersymbol Interference.* IEEE Trans. on Communications, 20(8), pp. 774–780, August 1972.

[IEEE Com. Mag. Aug. 1992] *IEEE Communications Magazine*, 30(8), Special Issue on ISDN, August 1992.

[IEEE Com. Mag. May 2000] *IEEE Communications Magazine*, 38(5), Special Section on "Very High-Speed Digital Subscriber Line," May 2000.

[IEEE Com. Mag. June 2001] *IEEE Communications Magazine*, 39(6), Special Section on "The Emergence of Integrated Broadband Cable Networks," June 2001.

[IEEE Com. Mag. Sept. 2001] *IEEE Communications Magazine*, 39(9), Special Section on "Broadband Wireless Access Technologies and Applications," September 2001.

[IEEE Com. Mag. Dec. 2001] *IEEE Communications Magazine*, 39(12), Special Section on "Topics in Broadband Access," December 2001.
[IEEE Com. Mag. 2002] *IEEE Communications Magazine*, 40(4), Special Section on "Topics in Broadband Access," April 2002.
[IEEE Com. Mag. March 2003] *IEEE Communications Magazine*, 41(3), Special Section on "Optical Wireless Communications," March 2003.
[IEEE Com. Mag. May 2003] *IEEE Communications Magazine*, 41(5), Special Section on "Internet Access Through the Power Line Network," May 2003.
[IEEE 802.16] IEEE 802.16 Working Group on Broadband Wireless Access Standards, http://ieee802.org/16/.
[IEEE 802.3ah] IEEE 802.3ah Ethernet in the First Mile Task Force, http://www.ieee802.org/ 3/efm/.
[ITU-T G.991.1 1999] ITU-T Recommendation G.992.1. *Asymmetrical Digital Subscriber Line (ADSL) Transceivers.* July 1999.
[ITU-T G.991.2 2001] ITU-T Recommendation G.991.2. *Single-Pair High-Speed Digital Subscriber Line (SHDSL) Transceivers.* February 2001.
[ITU-T G.992.2 1999] ITU-T Recommendation G.992.2. *Splitterless Asymmetrical Digital Subscriber Line (ADSL) Transceivers.* July 1999.
[ITU-T G.992.3 2002] ITU-T Recommendation G.992.3. *Asymmetrical Digital Subscriber Line (ADSL) Transceivers-2 (ADSL2).* July 2002 (Draft).
[ITU-T G.994.1 2003] ITU-T Recommendation G.994.1. *Handshake Procedures for Digital Subscriber Line (DSL) Transceivers.* May 2003.
[ITU-T PF-R15 2003] ITU-T Temporary Document PF-R15. *G.shdsl.bis: Draft Text.* Perros-Guirec, France, August 2003.
[Song 2002] K.B. Song, S.T. Chung, G. Ginis, and J.M. Cioffi. *Dynamic Spectrum Management for Next-Generation DSL Systems.* IEEE Communications Magazine, 40(10), pp. 101–109, October 2002.
[Starr 1999] T. Starr, J.M. Cioffi, and P.J. Silverman. *Understanding Digital Subscriber Line Technology.* Upper Saddle River, NJ: Prentice-Hall, 1999.
[Starr 2003] T. Starr, M. Sorbara, J.M. Cioffi, and P.J. Silverman. *DSL Advances.* Upper Saddle River, NJ: Prentice-Hall, 2003.
[Stokesberry 1993] D. Stokesberry and S. Wakid. *ISDN in North America.* IEEE Communications Magazine, 31(5), pp. 88–94, May 1993.
[Tomlinson 1971] M. Tomlinson. *New Automatic Equaliser Employing Modulo Arithmetic.* IEE Electronics Letters, 7, pp. 138–139, March 1971.
[TS 101 135 2000] ETSI Specification TS 101 135. *Transmission and Multiplexing: High Bit-Rate Digital Subscriber Line (HDSL) Transmission Systems on Metallic Local Lines.* Version 1.5.3, September 2000.
[TS 101 388 2002] ETSI Technical Specification TS 101 388. *Transmission and Multiplexing (TM); Access Transmission Systems on Metallic Access Cables; Asymmetric Digital Subscriber Line (ADSL).* Version 1.3.1, May 2002.
[TS 101 524 2001] ETSI Technical Specification TS 101 524. *Transmission and Multiplexing: Access Transmission System on Metallic Access Cables: Symmetrical Single Pair High Bitrate Digital Subscriber Line (SDSL).* Version 1.1.3, November 2001.