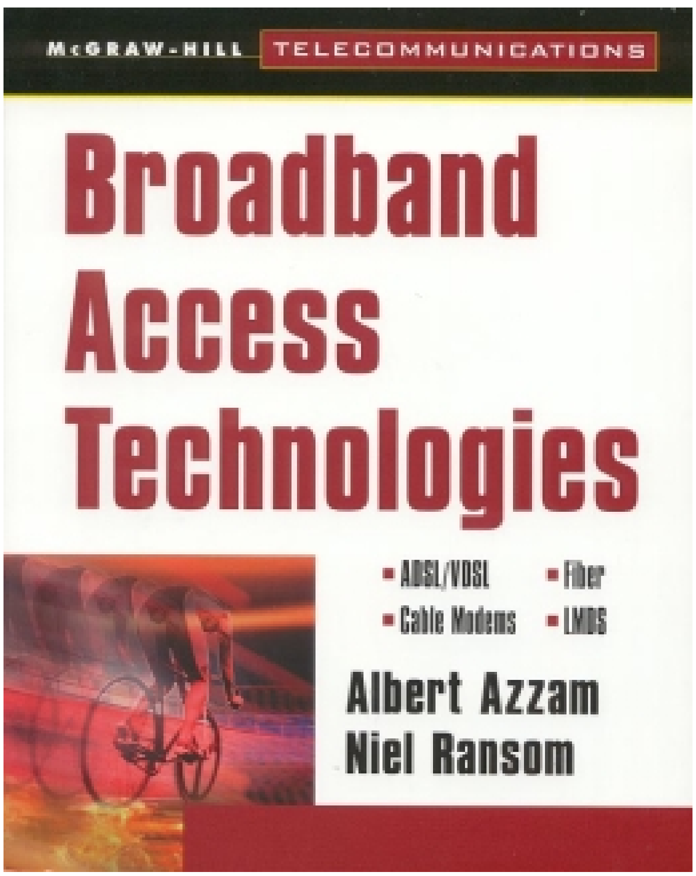
FURTHER READING:

As a preview for further reading, the following reference has been provided from the pages of the book below:

Title: Broadband Access Technologies
Author: Albert Azzam and Niel Ransom
Publisher: McGraw-Hill

ISBN: 0071350608



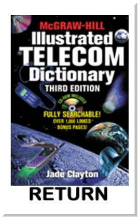
RETURN

Modem technology has at last reached its limit. Since the telephone network internally encodes voice connections at 64 kb/s, further increases of modem speeds on dial connections are not even theoretically possible. This limit, however, is imposed by the telephone switching systems and interoffice facilities; the lowly twisted pair copper wire to the home has yet more capacity to yield. In the 1980's, ISDN became the first system to exploit that capacity. ISDN transmits 144 kb/s in each direction over a single twisted pair of wires over 6000 m. At the central office switching system, this 144 kb/s is broken into two 64 kb/s switched channels and a 16 kb/s advanced signaling channel. Clever data communications engineers determined ways to dial the same end point with the two channels and combine their capacity to form a 128 kb/s connection. This may have been the savior of ISDN in North America. While in France and Germany ISDN was widely deployed for conventional telephone service, in North America ISDN languished awaiting a driving application, especially for residential customers. Many claimed that ISDN stood for ''I Still Don't Know.'' Recently, with the growing enthusiasm for the Internet, residential customers in North America have started ordering ISDN for fast Internet access.

The announcement of ISDN's success at last may have been premature. The demand has grown for even higher access data rates for residential customers to support new services such as web pages with video and multimedia components. Telcos still aspire for a means to offer switched Video-On-Demand services. All this is occurring in the context of increasing competition from CATV companies and new players in the telecom market brought about by the current telecommunications liberalization and deregulation. The telephone companies are again looking at the twisted pair copper wire to see if there isn't more capacity to exploit.

The amount of analog capacity on a twisted pair of copper wires is fundamentally related to its length. The majority of telephone loops are less than 4 km in length and yield a usable analog capacity of about 1 MHz. Shorter loops have even more capacity. Exploiting this capacity has been enabled by recent advancements in Digital Signal Processing technology.

ADSL (Asymmetric Digital Subscriber Line) provides one answer to this need. Recognizing that residential customers have a greater need for fast download speeds than for transmitting upstream data, ADSL devotes the majority of the capacity on the loop to the downstream channel. Depending upon the length of the loop, ADSL can achieve downstream bit rates up to about 7 Mb/s and upstream rates of several hundred kb/s. In this way, ADSL transforms the twisted pair from one limited to voice and low-speed data to a powerful wideband bit pipe. ADSL does all this while leaving the lower 3 kHz intact for support existing (analog) telephone service.



Although ADSL is a vast improvement over modems and ISDN and appears well-matched for high-speed Internet access, there remains a need for even higher capacities to support services such as Switched Digital Video Broadcast and even switched HDTV (High Definition TV). A conventional broadcast quality video signal, MPEG-2 encoded, requires 6 Mb/s. Given that many homes have multiple TV sets, a capacity of at least 12 Mb/s or 18 Mb/s is required. A single HDTV signal requires about 20 Mb/s. It turns out that even this is not too great for the copper loop. Using a technique known as Very High Speed Digital Subscriber Line (VDSL), 26 Mb/s can be transmitted on 3 km of copper loop and 52 Mb/s transmitted up to 1 km. This is much shorter than most subscriber loops. However, it can provide the ''last mile'' connection to Fiber-to-the-Cabinet (FTTCa) or Fiber-to-the-Curb (FTTC) architectures where optical fiber extends from the local exchange to the cabinet or the curb unit. Note that even for the high speeds of VDSL, the underlying analog POTS or ISDN service is maintained on the same twisted pair.

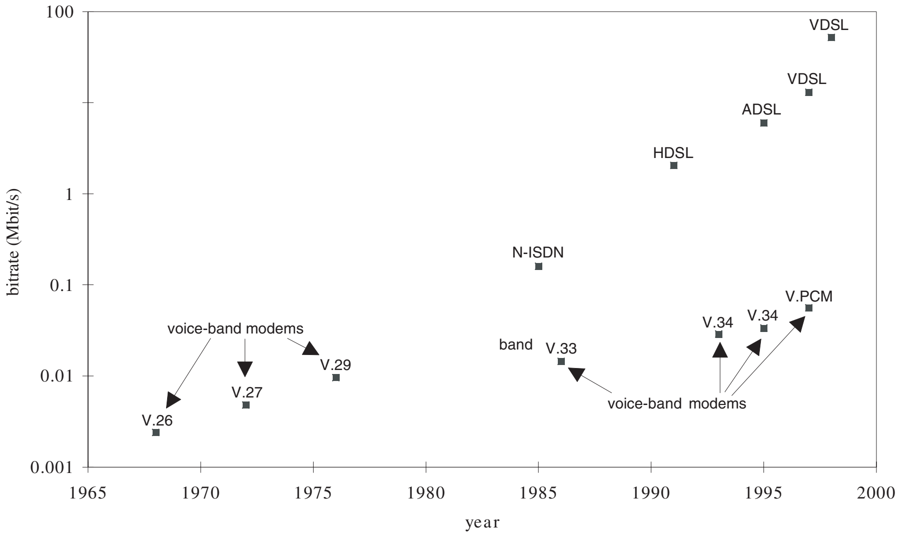
This chapter starts with an overview of the evolution of the capacity on copper twisted pairs. After a description of the main impairments of the medium, the chapter concentrates on ADSL and VDSL, covering the topology, the system requirements, the transmission techniques used and the current status in standardization.

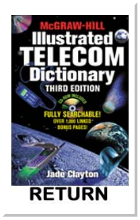
4.2 Evolution of Capacity on Twisted Pairs

Figure 4.1 depicts the evolution of transmission speeds on twisted pairs.

Since the early 1960's, voice band modems have been developed to transport digital data over the telephone network. With these modems, data is modulated at the transmitter, transported (bidirectionally over one pair or over two pairs) transparently through the telephone network and demodulated at the receiver. Different modulation techniques have been used, starting with FSK (Frequency Shift Keying) in the ITU-T standard V.21, DPSK (Differential Phase Shift Keying) in V.26, V.27 and V.29, to QAM (Quadrature Amplitude Modulation) in V.22bis, V.33 and V.34. Different duplexing techniques have been applied: full duplex transmission over a single pair with separated (FDD, Frequency Division Duplexing) or overlapping (EC, Echo Canceling) frequency bands for both directions of transmission, dual simplex transmission over two pairs and half duplex transmission over one pair. The

Figure 4.1
Evolution of Capacity on Twisted Pairs





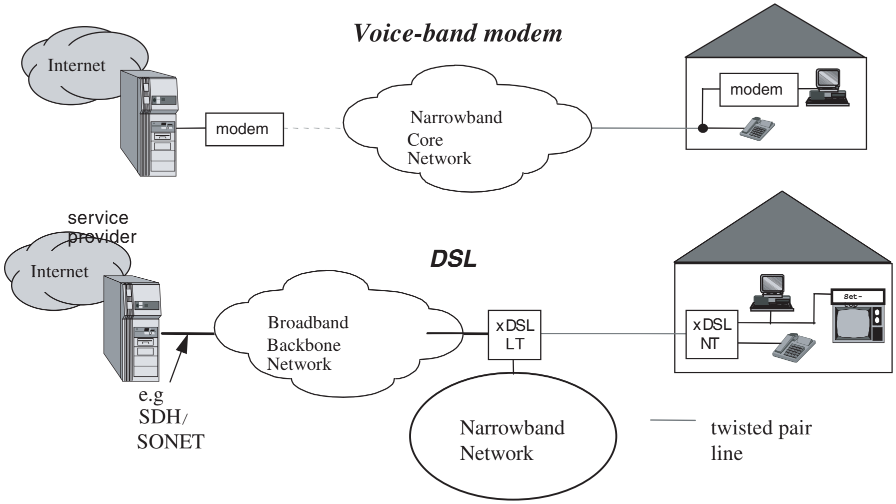
bit rates achieved range from 300 b/s in V.21 to 33.6 kb/s in V.34. More recently (in 1997), bit rates of 56 kb/s have been achieved (V.PCM [1]). However, these very high rates are only possible in the downstream direction and only in particular configurations, e.g., where an Internet service provider has a digital connection to the central office and where only one A/D converter exists in the connection.

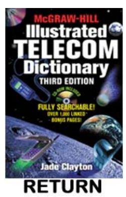
Key for voice band modems, as the name implies, is that the data is modulated in the voice band (from 300 to 3.4 kHz). This is a main difference with DSL modems whose spectrum is not limited to this band. The direct consequence is that DSL signals cannot be carried transparently over the POTS (Plain Old Telephone Service) network end-to-end. They have to be terminated before entering the local telephone exchange. Figure 4.2 depicts as an example of Internet access by means of voice-band modems (top) and ADSL (bottom). In case of the ADSL, the transmission on the twisted pair is terminated in the LT (Line Termination) on the local exchange and the NT (Network Termination) the subscriber side. The ''POTS-splitter'' in the LT separates the analog telephone signal from the digital data signal. The first is sent to the narrowband network (telephone exchange), the second to the broadband network (e.g. ATM switch or router).

A first step towards DSL was the introduction, in the 1980's, of basic rate ISDN that offers full duplex (EC) data transport at 144 kb/s (data plus sig-

[1] V.PCM is still in the process of standardization.

Figure 4.2
Voice Band Modem Versus DSL



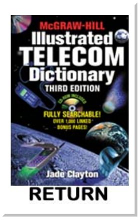


naling) over a single pair. The modulation format is 2B1Q (in North America) or 4B3T (in Europe). During the past years, the evolution in Digital Signal Processing techniques has enabled the design of several new modem technologies, such as HDSL, ADSL and very recently VDSL, boosting the transmission capacity of the existing twisted pair infrastructure. HDSL transports 1.5 Mb/s (North America) or 2 Mb/s (Europe) over 1, 2 or 3 pairs. The transmission on each pair is full duplex (EC). The modulation is 2B1Q. ADSL and VDSL are described in more detail later in this chapter. While HDSL is more suited for business applications, ADSL and VDSL primarily address the residential and SOHO (Small Office Home Office) markets.

It should be noted that besides those listed above, other DSL systems have been defined such as HDSL-2 (a single pair version of HDSL that is currently being standardized by ANSI/T1E1.4, sometimes referred to as SDSL) and RADSL (Rate Adaptive DSL, being the single carrier version of ADSL). Also, some proprietary systems have been announced: MDSL (Multi-rate DSL or Moderate speed DSL), UDSL (Unidirectional DSL) and IDSL (Integrated DSL).

4.3 Twisted Pair Impairments

The telephone access network consists primarily of twisted pairs of copper wires. (For a brief period aluminum wires were used in some countries, but



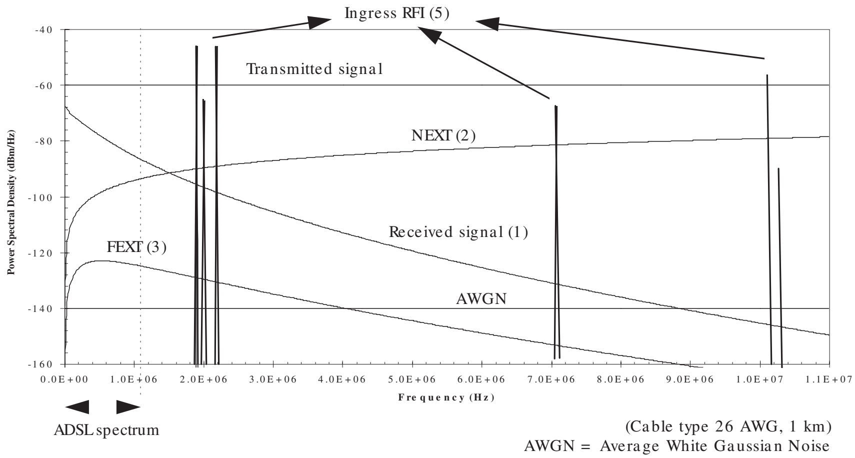
this conductor was not well-suited for this purpose as is a poorer conductor, is less pliable, and is more susceptible to corrosion). The twist in the twisted pair ensures equal coupling into the two wireless, thereby introducing few differential signals (longitudinal signals will not pass through coupling transformers at the end of the twisted pair). This also reduces electromagnetic radiation from signals carried in the copper loop.

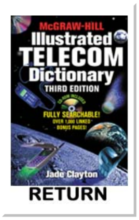
In the past, paper was used as an insulator between the wires. Today polyethylene is common. These wires pairs are combined in cables of different sizes ranging from a couple to a few hundreds of pairs. The cable structure can vary considerably. In Europe, the pairs are often combined in quads that consist of two pairs twisted around each other. These quads constitute binders of some tens of pairs. Finally, several binders are grouped in a single cable. In the U.S., this hierarchy is often non-existent and pairs are grouped in cables without forming quads. Between different wires in the same cable there exists capacitive and inductive coupling. The coupling increases as the wires are closer together. It causes unwanted crosstalk between the pairs. The crosstalk is typically worse between two pairs in the same binder than for wires in adjacent binders. It can be reduced by the optimization of the twist of the individual pairs and of the topology of the cable.

The transmission channel capacity depends highly on the twisted pair characteristics and suffers from a number of impairments.

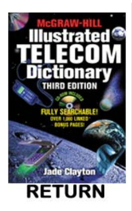
- Since the early days of telephony, load coils have been added to long loops (typically longer than 6 km) to boost and flatten the frequency response of the line at the upper edge of the voice band. In so doing, these coils greatly increase attenuation at frequencies above the voice band making them unusable for DSL. They must be removed to allow for DSL services.
- The frequency dependent attenuation and dispersion leads to pulse distortion and inter-symbol interference. In multi-carrier systems, inter-carrier interference can occur. Figure 4.3 illustrates the attenuation of the signal as a function of frequency after propagation over 1 km of 26 gauge twisted pair.
- Crosstalk between wire pairs in the same binder or adjacent binder groups is a principal noise contributor. Two types of crosstalk can be distinguished: Near-End crosstalk (NEXT) occurs at a receiver that is collocated with the disturbing source while Far-End crosstalk (FEXT) occurs at a remote receiver. FEXT is attenuated by propagation through the loop while NEXT is not. Therefore, NEXT dominates FEXT by far for echo canceled systems. Further, NEXT increases at a typical rate of 4.5 dB/octave ($f^{3/2}$) while FEXT increases by 6 dB/octave (f^{2}).

Figure 4.3
VDSL Signal and Noise Spectra





- In the process of connecting and disconnecting portions of the loop plant, sometimes a portion of open-circuited wire pair is left connected to a working wire pair. This is called a bridge tap. The existence of bridged taps in the loop plant differs from country to country and depends upon the cabling rules used in the past. Their presence causes reflections and affects the frequency response of the cable leading to pulse distortion and inter-symbol interference.
- A loop can also be built up of wires with differing diameters (referred to as gauge transitions), leading to reflections and distortion.
- Copper transmission suffers from impulsive noise that is characterized by high amplitude bursts of noise with a duration of a few microseconds to hundreds of microseconds. It can be caused by a variety of sources such as central office switching transients, ringing, ring trip, dial pulses and lightning.
- The impedance mismatch between the line impedance and the hybrid transformer (used to interconnect the bi-directional transmission of the loop to the separate transmit/receive path in the network) causes signal reflections. This problem can be resolved either by echo-cancellation or by separation of upstream and downstream transmission on the loop by means of Frequency Division Multiplexing (FDM).
- As a result of the cable unbalance, RF (Radio Frequency) signals can be picked up during propagation over the wire and interfere with the transmitted data at the receiving side. The balance of the cable decreases as the frequency increases. The aerial drop wires, the vertical cables in high-rise buildings and the in-house wires are the most vul-



nerable for RF ingress. This ingress can come from a variety of sources such as AM broadcast (LW, MW and SW), radio amateur communication and public safety and distress bands. The radio amateur is the most troublesome interferer for many reasons.

Because of the wide differences in network topology, installation practices and cable types, the impact of these impairments can vary significantly from operator to operator. Also, some DSL systems will suffer more than others from given impediments. As an example, RF interference is a much greater threat for VDSL than for ADSL because of its spectrum allocation (see section 4.5). In any event, a highly adaptive transmission system is needed to cope with the above imperfections.

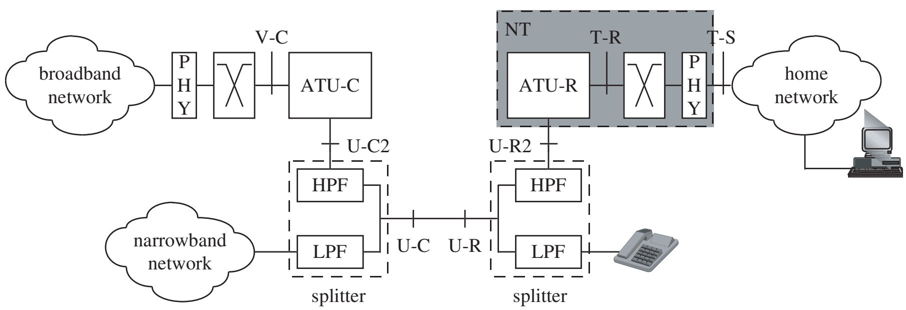
4.4 ADSL

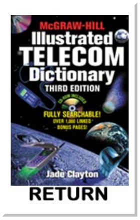
4.4.1 System Requirements Reference Model

Figure 4.2 (bottom) depicts a network reference model for ADSL. A somewhat more detailed view is given in Fig. 4.4.

ADSL has to coexist with POTS on the same pair. A POTS-splitter consisting of a low-pass filter (LPF) and a high-pass filter (HPF) separates the analog telephone signal from the digital data signal. The high-pass filter may be integrated with the ATU (ADSL Transceiver Unit) at central office side (CO) or the remote terminal (RT) side, i.e. the customer side. At the customer's premises, the low-pass filter is typically installed at the entrance of the home, i.e. in the basement or in the NID (Network Interface Device).

Figure 4.4
ADSL System Reference Model





4.4.2 Performance

The ADSL transmission system offers an asymmetric capacity to the subscriber. In the downstream direction (towards the subscriber), it provides a capacity up to 7 Mb/s, while in the upstream direction it provides up to 640 kb/s. In general, the maximum ADSL data rate depends upon the distance covered, wire gauge, and interference as shown in Table 4.1 (for uniform cable sections). The values in this Table are for DMT based modems. Single carrier modems have a different performance.

4.4.3 Transfer Mode

Three types of data transport are provided for in the ADSL standard:

- bit synchronous data such as DS1 (1.544 Mb/s) or E1 (2.048 Mb/s)
- packet data (e.g. making use of the HDLC protocol)
- ATM (Asynchronous Transfer Mode) transport

Provisions are made in the standard for the transport of each of these data types but the support of all three modes is optional.

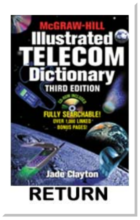
4.4.4 DMT Transmission

DMT transmission for ADSL has been standardized in ANSI/T1E1.4 and is supported by ETSI/TM6.

TABLE 4.1

ADSL Performance Figures

Reach	Cable (AWG)	Downstream Data Rate	Upstream Data Rate
18,000 ft	24	1.7 Mb/s	176 kb/s
13,500 ft	26	1.7 Mb/s	176 kb/s
12,000 ft	24	6.8 Mb/s	640 kb/s
9,000 ft	26	6.8 Mb/s	640 kb/s



4.4.5 Spectrum and Bit Allocation

The basic principle of DMT is to transmit the information bits in parallel over a large number (256) of carriers (tones), each of which is QAM modulated. The carrier frequencies are multiples of the same basic frequency (4.3125 kHz). For the separation of the up- and downstream transmission, two bandwidth allocation policies are included in the standard.

The first one uses overlapping spectra for up- and downstream transmission and applies echo canceling (EC). The second option uses frequency division duplexing (FDD) in which case no tones are shared by the up- and downstream bands. The latter is depicted in Fig. 4.5.

The upstream band ranges from about 25 kHz to 138 kHz (carriers 6 to 32) while the downstream band extends up to 1.104 MHz (carrier 256). The start frequency of the downstream spectrum can be anywhere above 25 kHz and is manufacturer discretionary. The lowest carriers are not modulated to avoid interference with POTS. The transmit power spectrum is almost flat over all used tones. For up- and downstream transmission, the average nominal psd (power spectral density) is respectively −38 dBm/Hz and −40 dBm/Hz across the whole band. In downstream direction, a power cut-back is applied on short lines to avoid saturation of the remote receiver. An optional power boost (of 6 dB) for long lines was provided in T1.413 Issue 2 to reduce the crosstalk to other services in the same cable. The passband ripple shall not be greater than ±3.5 dB. The number of bits that is assigned to a tone and its precise transmit power is determined during system initialization as

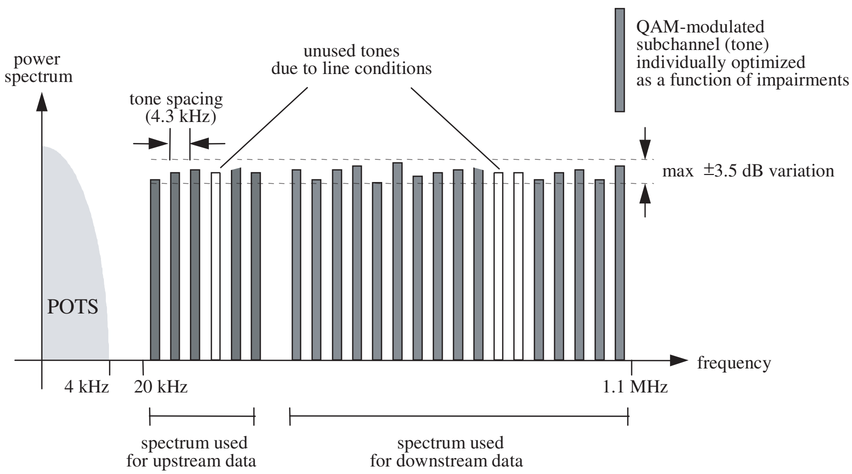
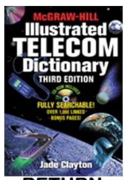


Figure 4.5
Transmit Spectrum of DMT-based ADSL Systems



a function of the SNR (Signal to Noise Ratio) on that tone and the requested overall bitrate. During operation, adaptation of the bit assignment or corrections to the transmit power are possible to compensate for alterations in line conditions, due to a variation of the noise or a (slow) drift of the cable transfer function (e.g. because of temperature variations). These on-line adaptations do not interrupt the data flow.

4.4.6 Error Correction

In order to improve the Bit Error Rate (BER) or (equivalently) to increase the system performance, expressed as an increase in capacity for a given BER, Forward Error Correction (FEC) is applied. ANSI specifies the use of Reed-Solomon (RS) coding combined with interleaving. The additional use of Trellis coding is optional but may further reduce the BER or increase the SNR margin.

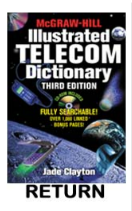
A distinction is made between delay sensitive or ''fast'' data, for applications as video conferencing or TCP/IP sessions, and delay insensitive data, such as for Video On Demand (VOD). Delay sensitive data is not interleaved and is transmitted within less than 2 ms (one-way). Delay insensitive data is interleaved to make it more robust against impulsive noise at the cost of increased latency. The ANSI standard allows for simultaneous transport of ''fast'' and interleaved data.

4.4.7 Bit Rate Adaptation

In T1.413 Issue 2 compliant modems, the up- and downstream bitrates can be programmed in any multiple of 32 kb/s. This small granularity is characteristic for DMT transmission. An increment (or decrement) of the bit rate with 32 kb/s is achieved by the allocation of one extra (respectively one less) bit on a single carrier.

At startup of the modem, two strategies are possible:

1. Manual rate selection (mandatory capability): The system starts up at the rate fixed by the operator. This can be done in accordance with the type of service the user is requesting (and paying) for.
2. Automatic rate selection (optional capability): At startup, the modem *itself* determines the transport capacity of a specific line and initializes at this rate. This concept has also been referred to as ''Rate Ad-



aptation at Start-up'' or ''Available Bit Rate'' ADSL as it maximizes the throughput of each individual line. The operator keeps control over essential parameters as delay, BER and SNR margin.

In an informative annex, T1.413 Issue 2 describes Dynamic Rate Adaptation (DRA). Its purpose is to allow reconfiguration of the modem during data transport and to avoid a lengthy restart procedure if the channel conditions or the service requirements would change over time. The mechanism allows rate modifications (up- and downgrades) for both up- and downstream as well as a redistribution of capacity between the fast and interleaved paths. However, these adaptations might involve a service interruption of the order of tens of milliseconds.

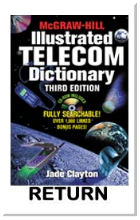
4.4.8 Characteristics of ADSL

The most important feature of ADSL is that it can provide high speed digital services on the existing twisted pair copper network, in overlay and without interfering with the traditional analog telephone service (plain old telephone service: POTS). ADSL thus allows subscribers to retain the (analog) services to which they have already subscribed. Moreover, due to its highly efficient line coding technique, ADSL supports new broadband services on a single twisted pair.

As a result, new services such as high speed Internet and On–line Access, Telecommuting (working at home), VOD, etc., can be offered to every residential telephone subscriber. The technology is also largely independent of the characteristics of the twisted pair on which it is used, thereby avoiding cumbersome pair selection and enabling it to be applied universally, almost independent of the actual parameters of the local loop.

The asymmetric bandwidth characteristics offered by the ADSL technology (64–640 kb/s upstream, 500 kb/s – 7 Mb/s downstream) fit in with the requirements of client–server applications such as WWW access, remote LAN access, VOD, etc., where the client typically receives much more information from the server than it is able to generate. A minimum bandwidth of 64–200 kb/s upstream guarantees excellent end-to-end performance, also for TCP/IP applications. These basic characteristics are reflected in two important advantages of the ADSL technology:

- No installation is required for laying new cables, making it useful solution in advance of fiber deployment in the local loop.



- ADSL can be introduced on a per-user basis. This is important to the network operators for it means that their investment in ADSL is proportional to the user acceptance of high speed multimedia services.

The mature ADSL product combines the benefits of the DMT and ATM technologies, resulting in:

- Full bandwidth flexibility: upstream and downstream bit rates can be chosen freely and continuously up to the maximum physical limits. At initialization, the system automatically calculates the maximum possible bit rate, with a predetermined margin. The service management system can then set the bit rate to the level determined by the customer service profile, thus maximizing noise margin and/or minimizing transmit power.
- Full service flexibility: a random mix of services with various bit rates and various traffic requirements (guaranteed bandwidth, bursty services) can be supported, within the available bit rate limits.

4.4.8.1 ATM Over ADSL. In addition to the total capacity of an ADSL line varying due to loop length and other factors, the bit rate required by the various services supported over ADSL will vary as well. Rather than attempt to define fixed capacity channels within ADSL matched to the envisioned services, it is better to use a flexible bandwidth management mechanism that is future safe; that can adapt to the changing needs of the services carried; that can provide the flexibility needed to support new services with bit rates other than those presently envisaged; and that can take advantage of changes in required bit rate resulting from improved compression technologies. A good example of the latter is MPEG 2 video services which can be sent with variable quality at bit rates from 1.5 to 6 Mb/s.

ATM offers the flexibility sought. Indeed, ATM is envisioned as the protocol base for future fiber-based access networks (such as APON described in chapter 3). By utilizing ATM on each of the advanced access network types, a uniform structure is created towards the user with the specific type of access network utilized affecting only the overall ATM capacity. This allows a clean evolution from the point of view of the subscriber and the service providers, from ADSL now, to VDSL in the near future, and eventually to fiber-to-the-home.

The ADSL units at the Central Office side and subscriber side are commonly referred to as ATU-C (ADSL Transceiver Unit, central office) or LT (Line