fast internet access by ADSL technology

via standard (copper) telephone lines

Since the early 1990s, it has been possible to interconnect a television receiver with the telephone system to provide a user interactive data service. A few years later, it was found that when Asymmetrical Digital Subscriber Line (ADSL) technology is used, a Video On Demand (VOD) service can be implemented. Since then researchers have discovered that ADSL provides an opportunity of significantly increasing the speed of access to the Internet. This article describes the basics of the ADSL technology and how it may be used to access the Internet at high speed.

By G. Kleine

INTRODUCTION

Unshielded twisted-pair copper wires as used in telephone networks to carry voice signals in the 300–3400 Hz band are capable of transporting much higher frequencies. This capability has already been used for some time in Local Area Networks (LANs) at data rates exceeding 10 MHz.

The line attenuation up to about 6 MHz is of the order of 0.7 dB/kHz with almost constant group delay. Because of this, there is very little pulse distortion to a digital signal and, therefore, very few bit errors.

These characteristics allow the frequency spectrum above the voice band to be used for a low bit rate (up to 64 kbit/s) for an upstream subscriber's control link and a downstream digital data service at rates exceeding 6 Mbit/s. Filters with high stop-band attenuation at each end of an ADSL network are, of course, required to use both bands simultaneously.

So as to limit the bandwidth needed, modern modulation techniques such as Carrierless Amplitude Phase (CAP) modulation as used for Group 2 fax machines, and Discrete Multi-Tone (DMT) modulation, are used. These techniques allow several bits to be represented by one transmission symbol. ADSL is named for this asymmetric bit rate allocation.

In Carrierless Amplitude Phase modulation, the bit stream is first split into two components and then separately passed through non-recursive digital filters that have an impulse response differing in phase by $\pi/2$. The outputs are then added, passed through a digital-to-analogue converter (DAC), and filtered before being passed to the transmission network.

Discrete Multi-Tone modulation is very similar to Coded Orthogonal Frequency Division Multiplex (COFDM) since the main channel is split into many sub-channels.

Each serial input signal is first encoded into parallel format and then passed through a Fast Fourier Transform (FFT) processor to convert the frequency-domain samples into time-domain values with a sliding time-window effect. These values are transcoded into a serial format and passed through a digital-to-analogue converter (DAC) before transmission.

The ADSL technology has been laid down in ANSI (American National Standards Institute) Standard T1.413.(1997).

FREQUENCY SPECTRUM

Currently, the most widely modulation used is DMT. As is to be expected, an ADSL-DMT signal consists of a great number of time-domain sub-channels that are superimposed on to the twisted-pair copper telephone wires. A diagrammatic representation of the resulting spectrum is shown in **Figure 1a**. The ADSL Standard provides for the frequency range of 0–26 kHz to be left free for the analogue telephone service (POTS = Plain Old Telephone Service – colloquial). The 26–1130 kHz band accommodates 256 sub-channels each 4.3125 kHz wide. The centres of these sub-channels are also separated by 4.3125 kHz.

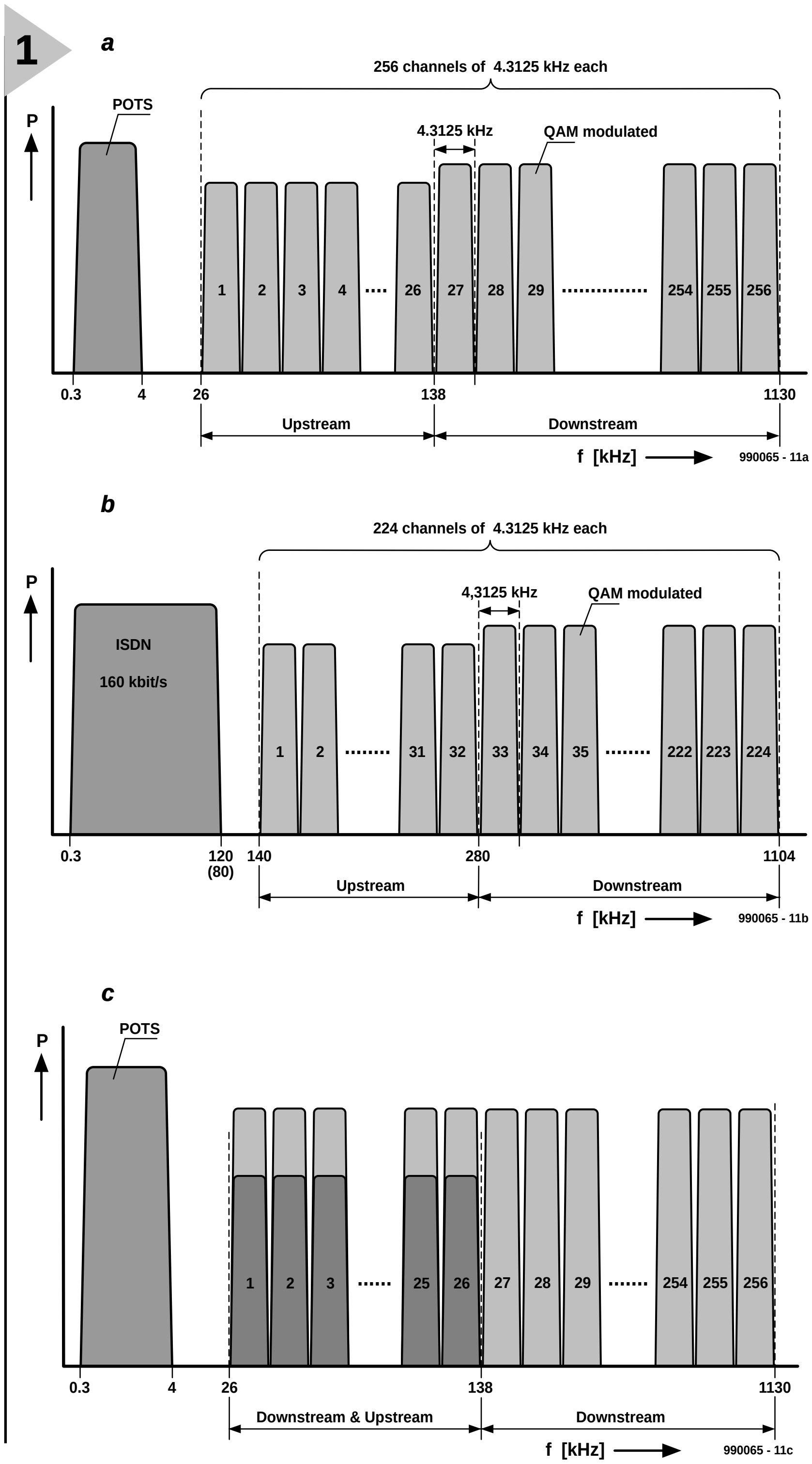


Figure 1. Spectrums with the use of ADSL technology:
(a) analogue telephony (frequency division multiplex—FDM)
(b) ISDN telephony (frequency division multiplex—FDM)
(c) analogue telephony (operation with echo compensation)

The individual carriers in the downstream and upstream ranges are quadrature amplitude modulated[1] and carry between 2 bit/s/Hz and 15 bit/s/Hz. The allocation of this rate of information is adaptive, that is, during the initialization process the individual carriers are allocated various signal spaces, depending on the noise in the relevant channel: (128-QAM, 64-QAM, 32-QAM, 16-QAM, 8-QAM, QPSK). The larger the signal-to-noise ratio, the larger the signal space and thus the number of bits representing a transmitted symbol.

Clearly, each channel in the signal can transmit up to 64.7 kbit/s, which, in theory, gives a maximum capacity of more than 16 Mbit/s in the case of 256 channels. However, in practice, owing to attainable signal-to-noise ratios, only about half of this capacity can be used.

When noise levels are high, or connection cables are very long, the signal space is reduced to an extent where secure communication is maintainable. This means that there may be channels which, owing to prevailing noise or high attenuation, are useless.

The standard foresees two possible means for allocating the channels to the downstream or upstream band: relatively straightforward Frequency

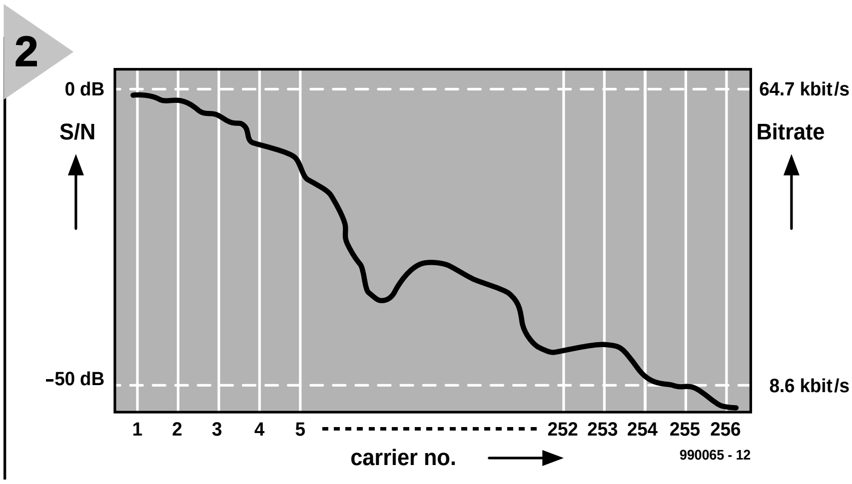


Figure 2. Bit distribution as a function of the signal-to-noise ratio.

Division Multiplexing (FDM) or Echo Compensation.

In FDM, the frequency range is split into two bands. The first 26 channels form the upstream band, while channels 27–256 carry the downstream data—see **Figures 1a** and **1b**.

In Echo Compensation, the frequency range is split into downstream and upstream according to the direction of transmission—see **Figure 1c**. This leads to a higher capacity for downstream data flow, since the lower 112 kHz of the ADSL range contains the better channels: at higher frequencies, the attenuation rises. So as to ensure that all functions well, an Echo Equalizer is needed, spaced well away from the remaining data flow. The ADSL Standard terms this mode of operation *Category 2 ADSL*.

Level differences may occur between the low frequency carriers and the high-frequency ones. If these do not exceed 50 dB, they are compensated by the channel equalizer in the ADSL modem. Higher attenuation would make the carrier ineffectual, were it not for the use of alternating line coding (in accordance with the prevailing signal-to-noise ratio) in conjunction with the channel equalizer in the modem. **Figure 2** shows a typical bit distribution as a function of the signal-to-noise ratio.

ADSL AND ISDN

Figure 1b shows the situation when an ISDN (Integrated Services Digital Network) access line is available. The signal on such a line (2×64 kbit/s) extends in some countries up to 80 kHz and in others up to 120 kHz. In order to make use of the ADSL technology, a way must be found to combine it with ISDN technology. This could, of course, be done by a switch to select between the two different usages, but this would mean that ADSL and ISDN would no longer be independent of one another and could not be used simultaneously. The solution adopted is for the DMT signal to start at 140 kHz instead of at 26 kHz. This means that, given a channel spacing of 4.3125 kHz, there are only 224 channels available. This is laid down as *Annex B* of the ADSL Standard.

The problem is caused by the fact that, in line with the ADSL Standard, the lower channels are used during the link set-up for testing the lines by means of test data packets, and for determining the bit rate of each individual channel. Since, in the case of ISDN, these channels are no longer available, channels in the upstream range are allocated for test purposes. All this is detailed in Annex B.

Since the lower channels are used for link set-up testing, they are nevertheless used in the domestic subscriber's system. They also ensure a secure first link between the ADSL modem and the end of the (telephone) trunk system. In the United Kingdom, most subscribers are within about 3 km (about 2 miles) of the end of the trunk system.

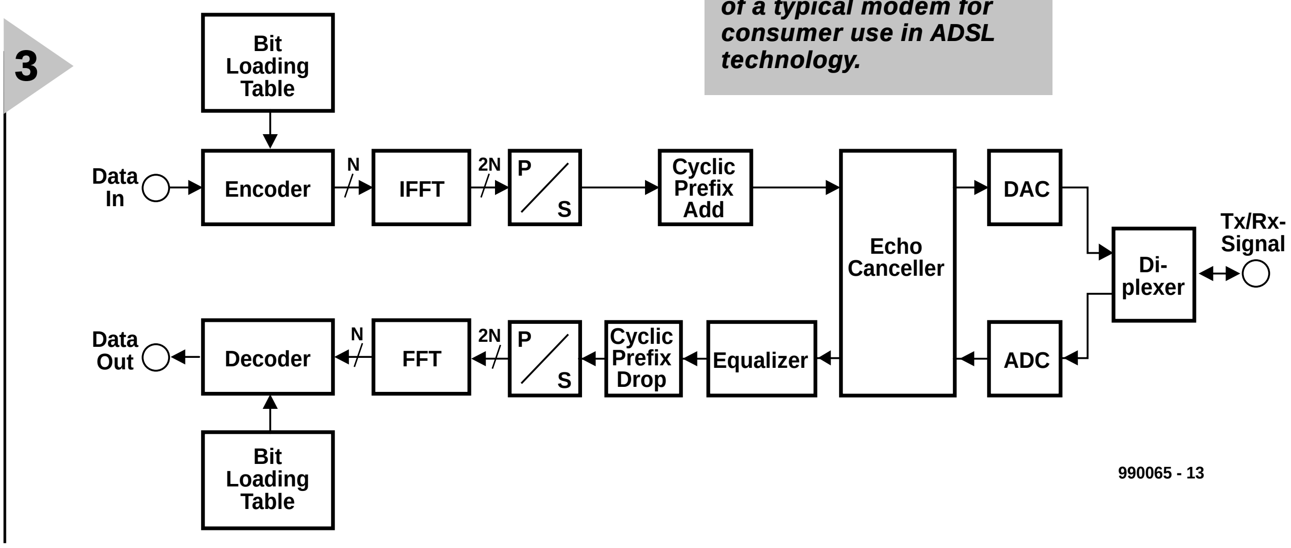
ADSL MODEM DESIGN

The design of a modem for use with ADSL is typically as shown in the simplified block diagram in **Figure 3.** A similar modem is also normally available at the telephone exchange, but there it can usually handle a number of subscribers and is called Digital Subscriber Line Access Multiplexer (DSLAM).

The incoming data (at the subscriber's end, the upstream data, and at the exchange end, the downstream data) are applied to an encoder, which allocates them to the *n* channels of the DMT signal. This is done in accordance with a bit loading table that has been established during the link set-up. This table shows how many bit/s each channel can handle. The encoder also provides Forward Error Control[2)] (FEC) with a Reed Solomon code (as used in digital television).

The parallel digital bit stream from the encoder is applied to an Inverse Fast Fourier Transform (IFFT) processor. This converts the *n*-bit wide frequency-domain samples into time-domain values (2*n* bits – real and imag-

Figure 3. Block diagram of a typical modem for consumer use in ADSL technology.



inary parts). These values are transcoded into a serial format, whereupon a cyclic prefix is added.

The echo canceller creates an image of the send and receive signals which blots up the real echoes when they come along. It is set up during the onset of the link with the aid of a test bit packet.

The output of the echo canceller is applied via a digital-to-analogue converter (DAC) and diplexer to the telephone line.

The incoming signal is applied via the diplexer to an analogue-to-digital converter (ADC) which converts the analogue signals on the telephone line into a digital data stream.

Subsequently, the signal is applied to the echo canceller which performs the same function as in the case of the outgoing data stream.

The equalizer, which is set up not only during the link set-up, but also during normal operation by means of test messages, provides requisite frequency equalization.

After the cyclic prefix has been removed, and the signal has been transcoded into parallel format, it is applied to the Fast Fourier Transform (FFT) processor. This stage reconverts the *n*-bit wide time-domain samples into frequency-domain values.

The decoder reconstructs the bits contained in the single DMT channels into the correct sequence by means of the Bit Loading Table with which it is programmed. The decoder also provides FEC with a Reed Solomon code which ensures that any bit errors are corrected.

Integrated circuit sets and other components for building an ADSL modem are available from many electronics retailers and mail order firms. Manufacturers of these parts are Motorola, STMicroelectronics, Alcatel, Broadcom, Globespan, and Texas Instruments. The web addresses of several of these manufacturers are given in **Table 1**.

The building of the modem presents constructors with a few challenges. For instance, the DMT signal needs very high gain amplifiers and linear operation of the power drivers. The crest factor is very high, which requires lots of reserve power in driver circuits. However, manufacturers like Burr-Brown and Analog Devices have special ICs available for these purposes. There are also problems in telephone exchanges, since each ADSL connection to a subscriber requires a power of 12 W. When many modems are contained, heat dissipation may become a problem.

ADSL EQUIPMENT

Figure 4 shows in diagrammatic form what an ADSL link entails at the sub-

Some abbreviations and acronyms:

AAL	ATM Adaptation Layer
ADC	Analogue-to-Digital Converter
ADSL	Assymmetrical Digital Subscriber's Line
ANSI	American National Standards Institute
ATM	Asynchronous Transfer Mode
ATU	ADSL Transceiver Unit
B-ISDN	Broadband ISDN
CAP	Carrierless Amplitude/Phase modulation
CDSL	Consumer Digital Subscriber Line
CODEC	COder-DECoder
COFDM	Coded Orthogonal Frequency Division Multiplex
CPE	Customer (subscriber) Premises Equipment
CRC	Cyclic Redundancy Check
DAC	Digital-to-Analogue Decoder
DMT	Discrete Multi-Tone modulation
DSL	Digital Subscriber Line
DSLAM	Digital Subscriber Line Access Multiplier
DTE	Data Terminal Equipment
DTMF	Dual Tone Multi Frequency
ETSI	European Telecommunications Standards Institute
FDM	Frequency Division Multiplexing
FEC	Forward Error Control (or Correction)
FFT	Fast Fourier Transform
IDSL	ISDN Digital Subscriber Line
IETF	Internet Engineering Task Force
IFFT	Inverse Fast Fourier Transform
IP	Internet Protocol
ISDN	Integrated Services Digital Network
ISO	International Standardization Organization
ITU	International Telecommunications Union
LAN	Local Area Network
MODEM	MOdulator-DEModulator
MPEG	Motion Picture Expert Group
N-ISDN	Narrowband ISDN
NT	Network Terminator
OSI	Open Systems Interconnection
PABX	Public Access Branch Exchange
PCM	Pulse Code Modulation
PDU	Protocol Data Unit
POT(S)	colloquial term for Plain Old Telephone System (or Service)
PSTN	Public Switched Telephone Network
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
SLIC	Subscriber Line Interface
TCP	Transmission Control Protocol
TDM	Time Division Multiplexing
UART	Universal Asynchronous Receiver/Transmitter
URL	Uniform Resource Locator
USB	Universal Serial Bus
UTP	Unshielded Twisted Pair
VADSL	Very high rate ADSL
VDT	Video Dial Tone: an alternative term to describe ADSL
VOD	Video On Demand
WAN	Wide Area Network

Some relevant Internet URLs:

ADSL Forum home page	www.adsl.com
Alcatel	www.usa.alcatel.com
ANSI home page	www.ansi.org
ATM Forum home page	www.atmforum.org
Broadcom	www.broadcom.com
ETSI home page	www.etsi.fr
Frame Relay Forum home page	www.frforum.com
GlobeSpan	www.globespan.net
Internet Engineering Task Force	www.ietf.org
ITU home page	www.itu.int
Motorola	www.mot-sps.com
St Microelectronics	www.st.com
Texas Instrument	www.ti.com.sc
Universal Serial Bus home page	www.usb.org

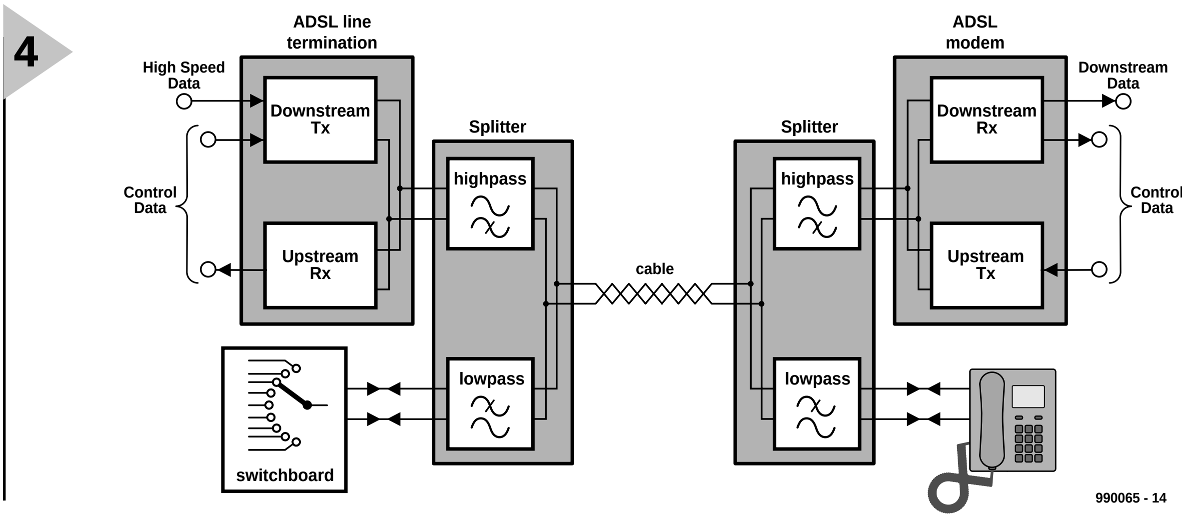


Figure 4. Simplified diagram of a typical ADSL system.

scriber's end and at the telephone exchange.

Immediately on entering the subscriber's premises and the telephone exchange, an ADSL splitter is needed. This contains a high-quality, high-pass filter with very steep skirts for the ADSL frequency spectrum.

The incoming or outgoing analogue telephone or ISDN signal, as the case may be, is passed through a low-pass filter.

At the subscriber's end, an ADSL modem must, of course, be available to which the output of the splitter is applied. This modem contains a receiver (Rx) for the high-rate downstream signal and a transmitter (Tx) for its own upstream signal. The upstream and downstream signals contain not only message data, but also management and control data.

At the telephone exchange, ADSL terminators must be added for each and every subscriber who wants ADSL service. These units are the opposite of a modem: a downstream sender (Tx) transmits the high-quality digital data stream via the splitter to the telephone lines. The upstream receiver (Rx) processes data at moderate rates. A Digital Subscriber Line Access Multiplexer (DSLAM) makes ADSL channels available to a number of subscribers.

ADSL SYSTEM STRUCTURE

Figure 5 shows in diagrammatic form what equipment other than an ADSL splitter and a modem are required. At the centre are the ADSL splitters in the telephone exchange and at the subscriber's premises.

At the exchange end, the output from the splitter is linked to the ADSL Termination and from there to the ATM (Asynchronous Transmission Mode) Backbone[3] via the ATM switch. The transmission rate between the line termination and ATM switch is 155 Mbit/s.

At the subscriber's end, the output of the splitter is applied to the ADSL modem, which contains an ATM-F25.6 interface (25.6 Mbit/s) or a (slower) LAN (Local Area Network) interface Type 10BaseT. The computer must contain a corresponding ATM or LAN card to be able to work failure-free with the modem interface.

In case an ISDN line is used, a Network Terminator (NT) must be inserted between the splitter and the ISDN connection—see **Figure 5**.

CONNECTION SET-UP

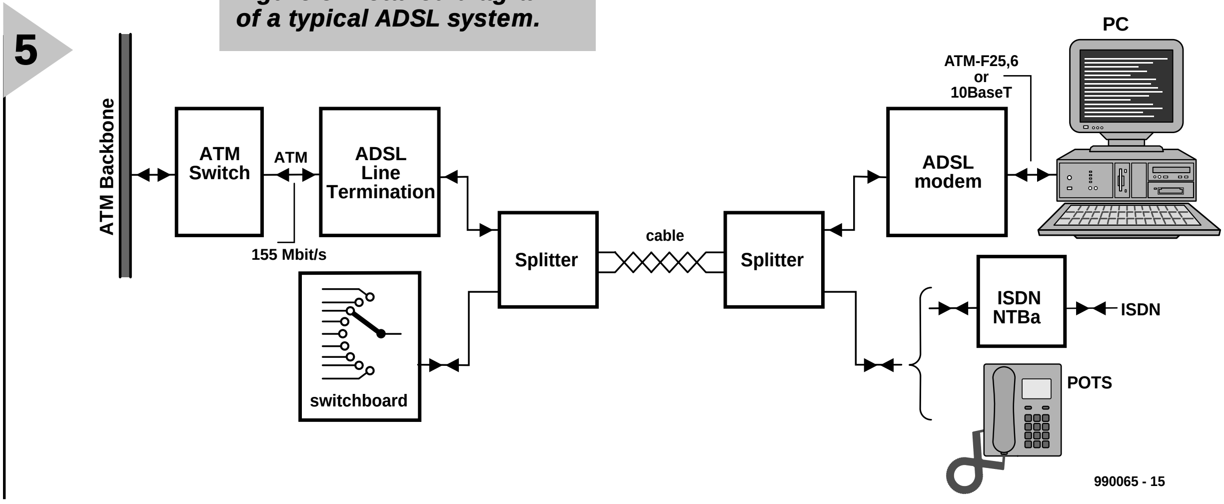
Owing to the many ways an ADSL transmission system may be set up, it is essential to study the protocol, specification, and any other relevant literature before starting the practical work.

The frequency response in both directions must be measured carefully and it should be ensured that the two modems use the same carrier frequency. Subsequently, the bit rates of the upstream and downstream channels should be determined, and also which means is to be used for channel allocation (FDM or echo compensation) with the aid of test messages. It is at this point that the maximum bit rate of individual connections is decided.

ADSL technology is capable of working with varying signal-to-noise ratios. Its Bit Swapping facility allows bits to be re-allocated to a specific channel during operation.

The start phase may take from 20 seconds to one minute. This slow beginning ensures, however, that the

Figure 5. Detailed diagram of a typical ADSL system.



maximum possible data rates for each and every channel are fixed optimally. If, for one reason or another, it is necessary to fix the bit rates anew, it is not necessary to wait again for 20–60 seconds before operation can start. There is a short procedure for this, which takes only a few seconds. In that case, it is, however, necessary for the modem to monitor the transmission quality of each and every channel.

ADSL LITE MODEM

Shortly after the ADSL Standard had been published by ANSI in 1997, a number of manufacturers, including Microsoft, Intel, and Compaq, formed the Universal ADSL Working Group (UAWG). One of the aims of this group was to get rid of the splitter, since this would mean a substantial saving at the exchange on the Subscriber Line Interface (SLIC) and at the subscriber's end on the ATM Ethernetwork card—see **Figure 6**. It should be borne in mind that the ADSL splitter is a costly unit. The consequent G.Lite or Universal ADSL modem is standardized by the ITU in the *ITU Standard G992.2 – Splitterless ADSL*.

Apart from the introduction of this modem, the number of channels is reduced from 256 to 128, the number of bits per second per Hertz is reduced, so that the signal space is smaller, the downstream bit rate is reduced to 1.5 Mbit/s, although the upstream can still be sent at 500 kbit/s. Furthermore, the output level is reduced to such an extent that power consumption and the requisite linearity of the analogue driver stages are moderated significantly. As a bonus, this also helps to keep the analogue telephone traffic almost entirely free of interference. And last, but not least, with an ADSL Lite modem, operation is in Category 2 of the ANSI Specification, which means that the upstream and downstream sections share the lower ADSL frequency range by means of echo compensation. This guarantees good transmission coefficients on the individual carriers.

It is interesting to note that splitterless ADSL technology is much more popular in Anglo Saxon countries than in continental Europe.

CONCLUSION

Now the ADSL technology has proved itself among commercial users, it is clear that it can lead to better use of the telephone system, particularly as regards access to the Internet, by domestic subscribers Even when downstream rates of only (!) 1.5 Mbit/s are attainable, this gives a 27-fold increase in data rates compared with those provided by a 56 kbit modem.

Current modems for domestic subscriber use are of the hybrid type, which can handle the V.90 analogue standard as well as the ADSL standard. Most of these modems can be adapted via firmware* in case of standard updates.

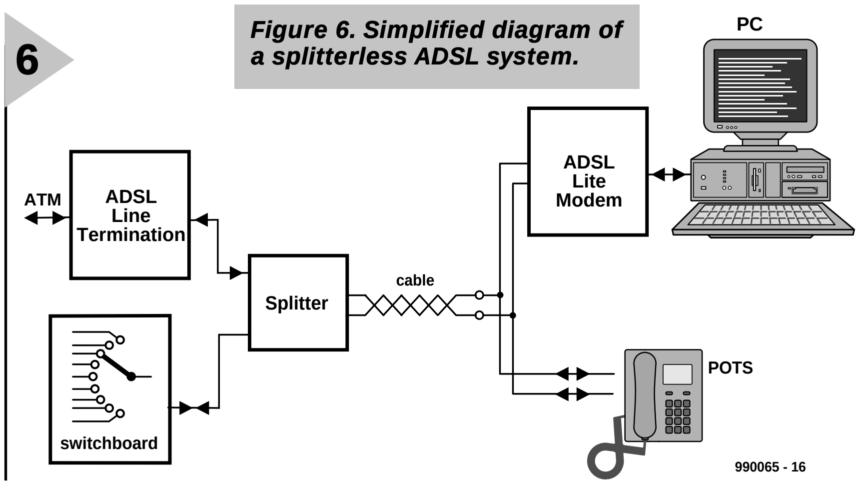


Figure 6. Simplified diagram of a splitterless ADSL system.

AND THE FUTURE?

Technology does not stand still, and already there are countries where Very high rate ADSL—VDASL—is being developed or market-tested. With the advent of fibre technology, the line impedance is being greatly reduced. This allows for very much higher bit rate services: currently expected to be 52 Mbit/s downstream and 3.2 Mbit/s upstream (with a copper tail of, perhaps, 100 metres) within a few years' time. Such rates will make MPEG-2 data transmissions possible.

[990065]

Notes:

1) Quadrature Amplitude Modulation (QAM) digital is a variant of Quadrature Phase Shift Keying (QPSK). In QPSK, quadrature phase shift of the carrier is used to convey two bits of data in the same bandwidth as one bit. In QAM digital, this is extended by obtaining 8, 16, 32, 64, 128, 256 phasors from the same carrier frequency to represent 8, 16, 32, 64, 128, 256 unique binary code patterns, each of 3, 4, 5, 6, 7, 8 bits.

2) Forward Error Control (or Correction) is a technique in which the means to detect bit errors is contained within the transmitted message stream thus allowing the receiver to correct the errors without requiring retransmission of the data.

3) It should be noted that echo cancellation is beneficial only whenever the same frequency is used for bidirectional traffic .When different subchannels are used for different directions, echo cancellation is superfluous. In that case, the UTP becomes three access points: one for speech, one for upstream data, and one for downstream information.

4) The backbone is the major transmission path of a Public Data Network (PDN).

5) Strictly speaking, firmware is system software held in read-only memory (ROM).

References:

ANSI T1.413: Network and Customer Installation Interfaces – Asymmetric Digital Subscriber Line Metallic Interface. Issue 1, 1995. Draft Issue 2, December 1998.

RFC 791: Internet Protocol

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ITU G992/2 (G.lite) Splitterless Asymmetrical Digital Subscriber Line (ADSL) Transceivers.

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