ABSTRACT

The Internet has surfaced as the dominant early market for residential broadband. ADSL, a transmission system capable of realizing rates from 1 to Mb/s over existing telephone lines, fits Internet access requirements perfectly, and offers telephone companies a tool for connecting virtually all Internet users at megabit rates before the next century. ADSL is asymmetric — high-speed downstream, lower-speed upstream — to counteract speed limitations imposed by line length and crosstalk. The transmission technology itself has two essential forms, single-carrier and multicarrier, which must press Shannon's limit to squeeze so many bits through so little bandwidth. With complicated line coding and other features such as integral forward error correction and ATM/Ethernet mode interfaces, ADSL will be the most complex modem ever attached to a telephone line. This will not prevent ADSL from reaching consumer-level pricing within the next two years. We can expect some commercial deployment in 1997 and virtually ubiquitous availability by the end of 1999.

Asymmetric Digital Subscriber Line: Interim Technology for the Next Forty Years

Kim Maxwell, Independent Editions

After much backstage preparation, asymmetric digital subscriber line (ADSL) is about to burst through the curtain. It will take a short bow, wait for a few protocol props left behind (financing came too late to get a full dress rehearsal), and stumble around for awhile as editors put in last-minute changes. But then ADSL will do its act, to multiply by the millions, and carry megabit data to users around the world over their existing plain old telephone lines.

This article offers a glimpse of ADSL as it is today, just about ready for that first bow. It will be broad, a brief technical taste of the ADSL world, inside and outside the modem. Readers frustrated by the consequent failure of depth can find all they need in the reference works on some subjects, but some important parts of the ADSL act still await final lines. For this we should be glad. We are innovators, after all, not historians.

WHY SHOULD WE CARE?

In 1993 many telephone companies were agog about fiber/coax. Seen as a competitive response to imminent competition from cable television (CATV), HFC would hit the streets running in 1994 and be in full deployment — many millions of lines a year — by 1996.

It is now 1996, and HFC has virtually died as a strategic component of next-generation access networks. HFC costs grew and grew (and still grow), and HFC bandwidth cannot support a full range of services to all customers. Furthermore, no single idea has taken its place, and telephone companies seem far more committed to service-specific networks than any near-term rollout of a full-service network. The reason is not obscure. The only new broadband application with universal appeal is video on demand. With today's technology, video on demand cannot generate enough prospective revenue to justify new infrastructure, and this equation is likely to hold for several more years. Therefore, telephone companies consider, and plan to deploy, MMDS, LMDS, fiber to the curb (FTTC), fiber to the node (FTTN), fiber to the home (FTTH), some HFC (often with purchased CATV companies), SDV, and ADSL, each to specific market segments; they hope that the various fiber alternatives can migrate to a full-service network over time.

ADSL would not have been on this list three years ago. ADSL runs at megabit rates — up to 9 Mb/s downstream and up to 1 Mb/s upstream — over existing copper telephone lines. Copper was scorned three years ago, a retrograde, rear-view-mirror technology with limited capacity and hopefully limited life, to be shuffled off this mortal coil without ceremony. That copper connects 700 million locations (and serves well over a billion users), and constitutes the last mile and largest single expense for an industry ringing up $750 billion in annual sales, seemed as irrelevant as wolves baying at the moon.

What happened?

The Internet. To the surprise of many, the Internet has rocketed into such prominence that simply uttering the word before securities analysts doubles a company's stock price. In simple terms, the Internet is a widely dispersed packet-mode cloud suffering, now, from too many subscribers, too little backbone bandwidth, slow routers, low server bandwidth, and miserable access speeds. This is a perfect context for ADSL. Assuming the Internet itself grows suitably (and it must), ADSL instantly increases access speeds by two orders of magnitude, to rates likely to be faster than the Internet itself can support for a number of years. Copper already connects all Internet users. Once ADSL access networks reach maturity (by 1998), ADSL can be deployed so fast that virtually all U.S. prospects can be connected by the year 2000. And the most important feature of ADSL access is that realistic revenue projections exceed costs from the outset. Indeed, it is not hard to make a strong case for ADSL serving tens of millions of customers and being around as long as copper, that is, for decades. As Ray Smith of Bell Atlantic opined, "ADSL is an interim technology, for the next forty years."

ADSL, however, does not stand for All Data Subscribers Living — it will not work over every telephone line, and certain telephone line parameters limit ADSL rate and performance. Grasping ADSL technically requires some

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understanding of these parameters. So this essay will begin with what exists, the telephone plant.

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THE TELEPHONE PLANT

The so-called subscriber loop plant of telephone companies today consists primarily of unshielded twisted pair copper access lines with passive premises terminations. In some countries, notably Germany, as much as 5 percent of the loop pPlant is digital, with active integrated services digital network (ISDN) terminations. In the United States (and some other countries), approximately 15 percent of the loop plant terminates the network side of copper lines in remote digital loop carrier (DLC) systems which multiplex voice lines over copper or fiber from an outside plant location to a central office. Of the 700 million lines operating today, about 70 percent serve residences, with the balance serving businesses. The United States today has about 160 million access lines.

Twisted pair copper attenuates signals proportional to length and frequency. If lines get sufficiently long (about 15,000 ft for 26 gauge wire, 18,000 ft for 24 gauge wire), their cumulative dc impedance begins to affect voice quality and dc signaling reliability. To compensate (in the United States. at least), telephone companies install loading coils in the line that effectively filter all frequencies above 4 kHz, and thereby bar any DSL service, including ISDN. Somewhere between 15 and 20 percent of all U.S. residential lines have loading coils. Long lines also attenuate across the band; the canonical 18,000-ft line has a 50 dB slope over the normal band of frequencies used for ADSL downstream data.

The figure of 18,000 ft has become a frequently cited normative bound for ADSL and ISDN, but it is a loose and fictitious one. It applies only to continuous runs of 24-gauge wire without bridged taps. There are almost no such lines in practice. Telephone companies pull 26-gauge wire, in bundles of 1000 or so lines, from central offices, and convert to 24-gauge about 10,000 ft out to improve impedance versus distance; rural areas may even see 19-gauge wire. DLC sites may encounter 24-gauge wire directly, but they seldom support lines longer than 9000 ft. Furthermore, plant cabling tends to come in 500-ft lengths, meaning a splice every 500 ft. Bellcore estimates that the average line has 22 splices; splice points collect corrosion and add attenuation if poorly made. Finally, many U.S. lines have bridged taps, a second (or third or fourth) unterminated spur off a line that may be quite short or thousands of feet long. Each bridged tap acts like a delay line and puts a notch in a line's frequency/attenuation characteristic at the frequency associated with a bridged tap's wavelength.

Attenuation dominates the factors limiting ADSL performance, but two other parameters have important effects: crosstalk and impulse noise. Alexander Graham Bell invented twisted pair wiring to, among other things, minimize coupling of signals from one pair to an adjacent pair when lines were bound together in a cable. The process is not perfect. Signals do crosstalk from one pair to another, at levels that increase with frequency and the number of crosstalking pairs, or disturbers. (The model used in ADSL standard T1.413 shows crosstalk increases proportional to frequency raised to the power 3/2 and to the number of disturbers raised to the power 0.6. Note, however, that new cables, such as UTP Category 5, improve crosstalk performance by as much as 20 dB over existing installed telephone wire.) As noted above, line attenuation also increases with distance and frequency. These factors drive the "asymmetric" nature of ADSL.

If a modem can realize 6 Mb/s on a given line, it can do so in both directions at the same time with suitable echo cancellation (the technique used in V.32 and V.34 to separate upstream from downstream channels). However, putting two such devices in the same cable will likely bring both to a halt. At both ends the adjacent transmit signal crosstalking into a local line above a certain frequency will essentially destroy the weakened local receive signal. This frequency, of course, depends on line length and gauge and the signaling complexity of the modem itself. But high-bit-rate DSL (HDSL), a symmetric service, transmits a duplex signal of no more than 750 kb/s (in a band of 240 kHz) for distances of 12,000 feet of 24 gauge wire (HDSL uses two lines and inverse multiplexing to achieve 1.5 Mb/s). Crosstalk prevents higher duplex rates with HDSL's line code.

ADSL beats this problem by sending in one direction only — downstream — with a much lower upstream rate separated from the downstream by frequency division multiplexing (some echo cancellation is possible at low frequencies). Current ADSL products use 25 to 250 kHz for the upstream, and 25 kHz to above one MHz for the upstream. As we shall see, the upper limit depends on the data rate and modulation system used. Note that an inverse ADSL with a high-speed channel going upstream (e.g., for an Internet server) must be disallowed. It will work, but it will either slow down or stop any other ADSL modems in the same cable with the conventional configuration.

Attenuation and crosstalk normally make up the canonical impairments for defining DSL performance. With crosstalk representing reasonable fill rates of a cable, the following downstream rates can be realized for the indicated distances of 24-gauge wire:

1.5 Mb/s	18,000 ft
2.0 Mb/s	16,000 ft
6.0 Mb/s	12,000 ft
9.0 Mb/s	9000 ft
13.0 Mb/s	4500 ft
26.0 Mb/s	3000 ft
52.0 Mb/s	1000 ft

The last three rates fall under VDSL rather than ADSL. As suggested above, 18,000 ft encompasses about 80 percent of lines in the United States. The region called the *carrier serving area* extends to 12,000 ft, and encompasses about 50 percent of lines in the United States. The faster rates on shorter loops will almost certainly be implemented in outside plant in various forms of fiber to the .... In addition, telephone companies will reach subscribers who fall outside the range of ADSL reach by installing fiber-based concentrator nodes, which will be stepping stones to deeper penetration of fiber into the loop plant.

Crosstalk noise is usually stationary. Impulse noise is random, in frequency, duration, and amplitude. As a result, it is difficult to model or study empirically. Furthermore, the impulse noise that arises in the telephone system has tolerable effects on voice communications and data communications using the 4 kHz voice channel available to ordinary modems. Thus, there has been little incentive to measure it or model it until recently. The picture emerging from the few field surveys published suggests that, while many impulses are small and short, a significant number, particularly those arising from ringing and trip ringing in adjacent pairs, can have destructive

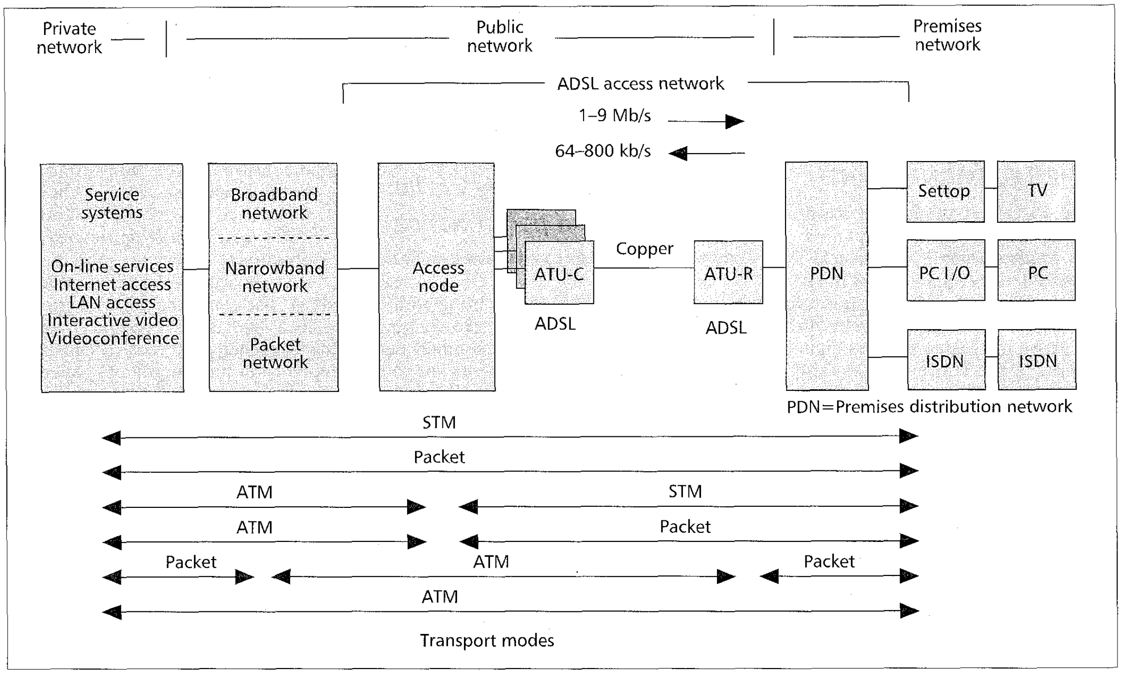


Figure 1. *ADSL network diagram.*

amplitudes for more than 1 ms. The DSL industry has a sort of working model now that shows 75 percent of all impulses with impulse width below 500 μs, and a pulse shape defined in T1.413, called a "Cook" pulse, that can easily be simulated. However, the real impulse world remains rather mysterious.

GETTING ORIENTED

Before launching into ADSL details, it will be worth taking one or two pictures from a few thousand feet up. Figure 1 shows the ADSL Forum Network Model. In essence, ADSL uses existing telephone lines to connect user terminals — personal computers and televisions — to various services over tandem combinations of public and private networks at much higher speeds than can be realized today with voice-band modems or ISDN. The public network part comprises an access node, for concentration and perhaps protocol conversion, and a switching or routing fabric. Access nodes may be located at central offices or in the loop plant at the end of a fiber link. Switching or routing facilities may be at central offices or buried deeper in the network. A controversy storms today about transport protocols — will Ethernet/IP or ATM dominate access node multiplexing? The pendulum seems to be swinging toward ATM, in which case the switching point will be in higher-level offices supporting numerous end offices and remote access nodes over fiber.

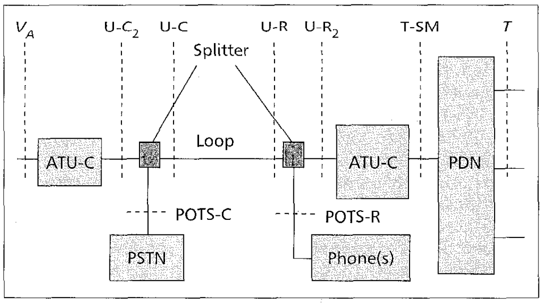
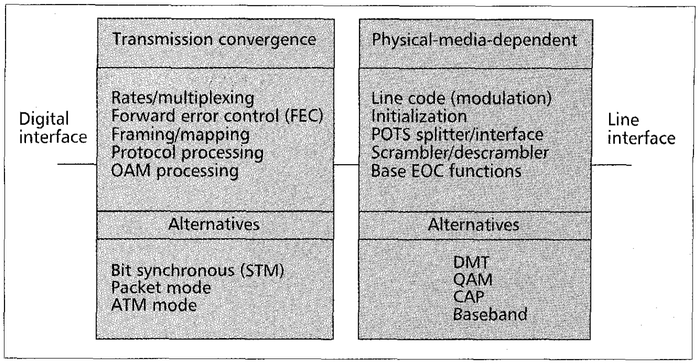


Figure 2. *ADSL system reference model.*

While the network side of this picture is complex, it has far fewer clouds hanging over it than the customer premises. These clouds linger above the innocent box called "premises distribution network," which can be anything from simple wiring to an Ethernet LAN to, sometime in the future, an ATM network connected to a residential gateway. It is not that any particular configuration stumps experts; it is that there are so many of them, all subject to the liabilities of customer installation. Unless an industry is developed to install premises networks, the inexpert user will be faced with piecing together ADSL with plain old telephone service (POTS) splitters, wiring, personal computers with or without network information center (NIC) cards, NIC cards, hubs, perhaps routers, and various software packages to pull usable data from whatever format ends up at the computer interface. (Prediction: such an industry will develop.)

Assuming telephone companies adopt a homogeneous ATM network to the premises, the most likely transport mode for the next few years will be the next to last shown in Fig. 1, with a large packet interface (such as frame relay) between the service provider and the public network and Ethernet between the ATU-R and the personal computer. The latter may use a Cells-in-Frame (CIF) protocol to tunnel ATM through a premises Ethernet. In any event, modems at both ends must be ATM-aware (cell pumps rather than bit pumps), and perhaps include some protocol conversion at the premises.

Figure 2 shows part of the ADSL Forum System Reference Model (a subset of the network model). At its center is the only thing that really exists in volume today, the telephone line. As ADSL shares this line with POTS, the first thing the line encounters on each end is a set of filters that split the line by frequency, a low-pass filter passing POTS and a high-pass filter passing ADSL signals at roughly 25 kHz and above. The POTS line goes off to telephones at the customer premises, and the public switched telephone network (PSTN) at the network end. How to accomplish this and not disturb either the quality or reliability of POTS is neither trivial nor completely solved today. The largest question mark concerns the U-R2 and U-C2 interfaces. The ADSL Forum has recommended, and T1E1.4 has agreed, that the POTS splitter should be physically separated from the modem (the roughly 10,000 ADSL units in the field today integrate the POTS splitter with the modem). This raises the rather difficult problem of defining an interface so a POTS splitter can be purchased from one vendor and a modem from another.



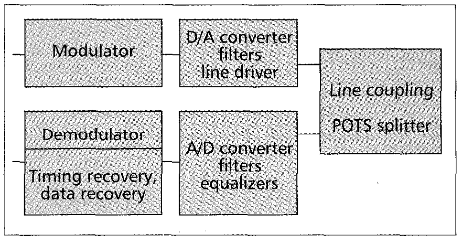
■ **Figure 3.** *ADSL functional layers.*

When Bellcore first conceived ADSL (1989), they envisioned a simple bit pump with a 1.5 Mb/s downstream rate and a 16 kb/s or 64 kb/s duplex channel for signaling and video controls, targeted at video-on-demand applications. Today some ADSL modems realize downstream rates of 9 Mb/s, upstream rates of 1 Mb/s, initialization protocols that will pick the best speed for a given line, and packet or cell interfaces that connect directly to Ethernet or ATM premises distribution networks. The simple bit pump is probably stillborn. Over its grave stands a suite of features sufficiently complex that standards groups are now considering a division of the basic modem into two layers — the physical-media-dependent (PMD) layer and the transmission convergence (TC) layer, following a similar division in ATM physical (PHY) layer protocols. Figure 3 suggests the divisions of functions for each layer and the various versions of each layer's implementation that might be considered.

PHYSICAL-MEDIA-DEPENDENT ADSL FUNCTIONS

The PMD section of ADSL represents what we would normally think of as a modem. Regardless of modulation technique, all ADSL transceivers perform the functions shown in Fig. 4. A modulator creates a digital representation of a signal modulated by the particular combination of transmit data bits during any given symbol period (inverse of the baud rate). An analog section converts this digital representation to analog, filters it, and then amplifies it to a level consistent with line power requirements. The receiver section essentially reverses this process, but must equalize the line to normalize the signal beforehand.

At present ADSL has three candidate modulation techniques, or line codes, making their way to the marketplace. One, discrete multitone (DMT), divides the line into many small channels and modulates each one based on its capacity for a given line; ANSI standards group T1E1.4 has developed an ADSL standard, number T1.413, around DMT. However, two major telecommunications suppliers have embarked on alternative line code implementations in an effort to seize early market share before the standardized line code matures into viable commercial products. Both use single carrier techniques — auadrature amplitude modulation (QAM), the mother of all ADSL line codes, and carrierless amplitude-phase modulation, AM-PM (CAP), a variant of QAM with some implementation and flexibility benefits over QAM; these are discussed in some detail below.

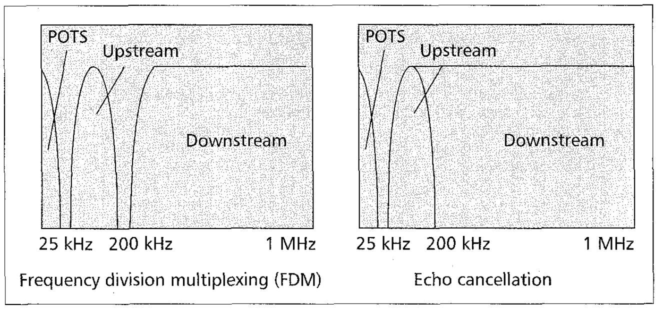


■ **Figure 4.** *Basic transceiver PMD layer.*

One normally begins a discussion of modems with rates and bandwidth: what rate does the line code have to realize over what frequency range? ADSL began in this conventional manner — downstream rates of 1.5 Mb/s over 18,000 ft of 24-gauge wire, 6 Mb/s over 12,000 ft of 24-gauge wire, assuming certain models of crosstalk interferers — but early in 1996 ADSL took an odd turn. Someone observed that ADSL was fishing for business in the Internet lake rather than the video sea. The Internet is inherently variable-rate, promises of real-time services notwithstanding. Interfaces to the network and to the home PC (not the television settop box) would be Ethernet or ATM, both variable-rate. Why not make ADSL variable-rate, offering the subscriber the best rate his line would allow, even if this rate fell below 1.5 Mb/s? The Internet wasn't going to run even that fast for most uses anyway for quite some time.

Now this idea has the blessed property of extending the number of telephone lines ADSL will work on without line engineering. It was consequently endorsed by telephone companies with remarkable rapidity. To avoid the image of ADSL adapting continuously to small line variations, "variable rate" was changed to "rate adaptive," giving rise to a new acronym, RADSL, for rate-adaptive DSL. RADSL modems will likely dominate the near-term market, particularly in the United States. Some countries still pursuing ADSL for video delivery will stay with fixed-rate ADSL. In practice, the two modems will also likely be the same, since fixed-rate ADSL can clearly be carved out of RADSL, and RADSL is, in practical terms, no more expensive than ADSL.

Rate adaptation is not restricted to the downstream channel. Some studies show that good performance on the Internet requires a downstream/upstream ratio of 10/1. While protocol tweaking and parameter negotiation can raise this ratio to, say, 20/1, the former figure has become an operating target. Thus, a downstream rate of 2 Mb/s needs an upstream rate of 200 kb/s, while a downstream rate of 6 Mb/s needs one of 600 kb/s. This sort of rate flexibility also extends to other services. For



▩ **Figure 5.** *Channel configurations.*

example, a user may want a video conference at 384 kb/s symmetric during one session and a very asymmetric movie needing 1.5 Mb/s during another session. A rate-adaptive modem (particularly one with echo cancellation) can rearrange the two directions to suit (subject to the limits imposed by line attenuation and crosstalk PSD masks).

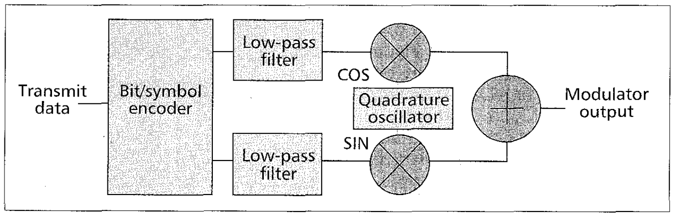
Figure 5 shows channel allocation for two basic ADSL modes. Each mode blocks off the lower 25 kHz for POTS (POTS only needs 4 kHz, but POTS splitters become very difficult to design if the lower edge of the upstream channel gets any closer). An upstream channel with usable bandwidth on the order of 135 kHz takes the next slot. This section of the channel has the most favorable attenuation characteristics, but also suffers the most crosstalk from other services such as ISDN DSL (with frequencies to 80 kHz) and HDSL (with frequencies to 240 kHz). In the rate-adaptive mode, oddly enough, the upstream channel may be the limiting resource rather than the downstream in some circumstances.

In frequency-division multiplexing (FDM) the downstream channel starts above the upstream, at approximately 240 kHz, and extends as far up as needed, or permitted, by a combination of desired data rate, attenuation, and modulation mode. As we will see below, a rate-adaptive single-carrier system can use bandwidths anywhere from 340 kHz to 1088 kHz to achieve data rates from 680 kb/s to 8.7 Mb/s, graduated in steps of about 320 kb/s. A multicarrier modem, with its channel slivers adapting to line conditions, may use frequencies out to 1.1 MHz (a band of 860 kHz): its rate range is from 32 kb/s to in excess of 9 Mb/s, graduated in steps of 32 kb/s.

In echo cancellation (EC) mode the downstream channel overlaps the upstream. This has two advantages, at the cost of the echo canceller: the downstream has more bandwidth in the good part of the line; and the upstream can be extended upward without running into the downstream. In practice the latter is the most significant benefit. At present only multicarrier ADSL modems have been implemented with echo cancellation.

SINGLE-CARRIER MODULATION

The parent line code for all ADSL is QAM. Of the various general modulation schemes available, QAM has the best combination of bandwidth efficiency, performance in the presence of noise, and timing robustness. (Other line codes, such as 2B1Q used in ISDN DSL and HDSL, have virtues, largely in relatively low complexity and cost.) As suggested by Fig. 6, a QAM bit/symbol encoder forms bit groups during each symbol period and then splits them into half rate streams that modulate a pair of orthogonal carriers, which are in turn summed to form the output waveform. The output band must be at least equal to the symbol rate (the baud rate), but timing recovery in the receiver often dictates some excess bandwidth, usually on the order of 15 percent. Thus, a 680 kbaud signal will use 782 kHz of bandwidth.



▩ **Figure 6.** *QAM modulator.*

Using this bandwidth efficiently comes from QAM's ability to assign increasing numbers of bits per symbol. A typical QAM system (say the one in V.32 for 9600 b/s) groups four bits per symbol, and requires a 21 dB signal-to-noise ratio (SNR) at the receiver to realize suitable error rates. However, QAM can be designed with fewer bits per symbol, and with more, up to 15. For each bit added the SNR must increase 3 dB to achieve the same error rate, and each bit added pushes implementation constraints on noise floors, D/A and A/D converters, and DSP processor bandwidth. However, practical QAM implementations today achieve 8 b/symbol, meaning, for example, that a 680 kbaud output transmits 5.44 Mb/s, but requires 33 dB SNR at the receiver.

Note: It is common to talk about signaling densities as bits per Hz, or bits per baud, or as the number of points in a constellation associated with a particular number of bits per symbol. Constellations usually have a number of points equal to 2 raised to the power of the bits per symbol. For example, 4 b/symbol is the same as 4 b/Hz and 16 QAM, and 8 b/Hz is the same as 256 QAM.

The problem and complexity for any single-carrier system for ADSL arises from how to adapt to wide variations in telephone lines. To work well, a QAM receiver needs an input signal with the same spectral shape and phase relationships as the one transmitted. Telephone lines change both; therefore, QAM receivers include adaptive equalizers that determine line characteristics and use them to compensate for distortion added during transmission. The process is not perfect, and the wider the range of possible distortions, meaning the wider the range of lines, the more complex the equalizer must be. Indeed, for ADSL the adaptive equalizer dominates system complexity for QAM implementations.

AT&T has developed a variation on QAM, called carrierless AM-PM or CAP, which generates a transmit waveform by applying each half-rate bitstream to a pair of digital transversal bandpass filters with equal amplitudes but phase responses differing by $\pi/2$. This produces the same spectral shape as QAM, may be detected with the same equalization strategies, and has the same performance as QAM. Indeed, a QAM receiver can be modified to receive a CAP transmit signal. CAPs virtue lies in some efficiencies compared to QAM with digital implementation.

The initial CAP systems for ADSL followed Bellcore's lead and implemented a single downstream rate of 1.5 Mb/s and an upstream rate of 64 kb/s. The latest proposed CAP system is rate-adaptive, from 640 kb/s to 8192 kb/s in the downstream direction and from 272 kb/s to 1088 kb/s in the upstream direction. To achieve reasonable granularity, the proposed CAP system implements five downstream baud rates with five

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