# How xDSL Supports Broadband Services to the Home

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**Abstract**

Why has xDSL suddenly achieved its present status as potentially the most promising of the broadband access technology options for both residential and business users? This article attempts to shed light on this question from both the technical and market perspectives. An overview of the family of xDSL technologies is provided, and a comparison is made to cable modem technologies. The evolution of xDSL regarding aspects of price, standardization, and interoperability is explored — demonstrating a strong technology push. Key factors of the ADSL business case are discussed — demonstrating a strong market pull. An overview of xDSL trials, applications, and network models is provided. The conditions are right for xDSL to advance rapidly to mass market adoption.

In the domain of wide area network (WAN) access, there are numerous technology options presently competing for market share and acceptance. These technology options originate from both the WAN and local area network (LAN) environments, and include integrated services digital network (ISDN), asynchronous transfer mode (ATM), ATM25, switched Ethernet, frame relay, several technologies for data transmission over coaxial cable television (CATV), and the family of digital subscriber line (xDSL) technologies.

In the past year, xDSL technologies have attracted a great deal of attention in the press as the access solution of the future in both the home and business application environments. Originally, xDSL technologies, operating over the existing infrastructure of copper wiring, were proposed as an intermediate access solution for the residential area before the extensive installation of a hybrid fiber coax (HFC) infrastructure or fiber to the home (FTTH). It has become apparent that the installation of an HFC or FTTH infrastructure will require a far larger investment and much longer deployment schedule (measured in decades) than previously envisioned. Therefore, the "intermediate" period of xDSL deployment may well be with us far into the 21st century.

Although xDSL technologies have seemingly "emerged" from data communications laboratories only recently, they have actually existed for a number of years — although without the notoriety they enjoy today. Why then has xDSL suddenly achieved its present status as potentially the most promising of the broadband access technology options for both residential and business users? This article attempts to shed light on this question from both the technical and market perspectives.

## The Essence of xDSL

For decades, conventional wisdom has held that analog modems would reach a 56 kb/s ceiling in terms of maximum possible bandwidth without compression. In actuality, the 56 kb/s threshold refers only to the amount of bandwidth that is theoretically possible over the audible spectra of frequencies. The audible spectra consists of only the bottom 4 kHz of total spectra available on a typical pair of telephone wire.

However, the entire spectra of frequency transmittable over copper wire is typically in the area of 1 MHz. The way xDSL technologies achieve their exponential increase over the analog modems common today is by exploiting frequencies above 4 kHz. These frequencies have not been used previously due to the difficulties they cause for normal transmission of voice traffic. Frequencies above 4 kHz transmitted over a pair of copper wires in a binder tend to disrupt plain old telephone service (POTS) by introducing unacceptable levels of near-end crosstalk to other wire pairs in the same binder.

xDSL technologies employ highly sophisticated techniques that limit near-end crosstalk and therefore greatly expand the bandwidth potential over a single pair of copper wires. As an added benefit, these techniques not only permit POTS service to continue unaffected over wire pairs in the same binder; they also permit POTS service to continue simultaneously on the same wire pair upon which xDSL transmission takes place.

These techniques have been made possible by the continuing advancement of lower-cost and more powerful digital signaling processing (DSP) chips, which require increasingly lower electric power. While the concept of utilizing the higher frequencies available on a telephone line for providing broadband access has existed for over a decade, it has only become feasible in the last five years due to developments in DSP technology.

In the early '90s, xDSL technologies (specifically asynchronous DSL, ADSL) were tested by some of the regional Bell operating companies (RBOCs) in the United States, as well as several European postal, telephone, and telegraph ministries (PTTs). Many of the tests gave birth to full-scale trials. However, at that time, the driving applications behind deploying xDSL were video on demand (VOD) and interactive TV (ITV). Those applications were seen as potentially explosive sources of revenue growth for the residential market. ADSL was the phone companies' delivery weapon against the CATV networks that were gearing up to deliver these services over their coaxial cable infrastructure.

Much to the disappointment of cable companies and telephone companies alike, both VOD and ITV failed miserably as "killer applications" that would justify a full-scale rollout of these services. At that point, ADSL was, to a large degree, forgotten.

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In 1995, interest shifted toward the on-line world and, more specifically, the World Wide Web. As has been clear from the beginning of the Web in 1993, far more bandwidth is required in order to make the Web a universally accessible "information superhighway," as well as to support the more demanding Web-based applications. The increasing demand for bandwidth with which to access the Web is one of the primary applications at which xDSL technologies are now targeted. However, xDSL technologies are also being looked at in conjunction with several other applications. These applications may produce a far greater revenue stream in the near term (i.e., 1997) compared to broadband Web access for the residential market. Among these applications are:

*Intranet Access* — For organizations that are standardizing on a Web-based, client/server model. An organization that has implemented an Intranet will require the higher bandwidth afforded by xDSL in order to link their remote office/branch office (ROBO) environments and telecommuters to the more demanding business-oriented applications running on their private Web servers.

*Low-Cost, High-Throughput, LAN-to-LAN Connectivity* — xDSL technologies have the potential to prove far more effective in this role than ISDN or traditional leased lines.

*Frame Relay Access* — Since xDSL operates at the physical layer, it could emerge as the most cost effective method of carrying frame relay traffic from the service subscriber to the frame relay network. Frame relay over xDSL serves the first two applications we have mentioned and greatly reduces the cost of using frame relay in other applications as well, such as carrying legacy mainframe traffic or even voice traffic.

*ATM Network Access* — As with frame relay, xDSL technologies can also be used to carry ATM cells to an ATM access device, where they are statistically multiplexed over an ATM backbone.

*Leased Line Provisioning* — xDSL can be used to greatly reduce the cost of provisioning T-1/E-1 lines from the central office (CO) to the customer's site.

*ADSL: Asymmetric Digital Subscriber Line* — While there are many flavors of xDSL technology, ADSL perhaps holds the greatest potential for mass deployment. Therefore, we will cover ADSL here in a separate section. In the past, ADSL has perhaps gained the most attention in the press as the flavor of xDSL that holds the greatest near-term potential for providing broadband access to residential and SOHO (small office, home office) markets. However, recently ADSL has been recognized as a potentially ideal solution for the corporate internetworking market, as well as the general consumer market.

As its name indicates, ADSL apportions bandwidth asymmetrically. That is, more bandwidth is allocated for "downstream" transmission (i.e., for traffic from the service provider to the subscriber) than upstream traffic (i.e., for traffic from the subscriber to the service provider).

ADSL achieves its asymmetrical bandwidth structure by dividing the local loop into four classes of channels: higher-bandwidth simplex (unidirectional) channels, lower-bandwidth duplex (bidirectional) channels, a duplex control channel, and a POTS channel, which occupies the lowest 4 kHz of frequency on the line. Transmission occurring on either the simplex or duplex channels does not affect the POTS channel. This ability to simultaneously provide POTS service alongside broadband data and/or video services across the same copper wire pair is one of ADSL's primary advantages relative to other access technologies, such as ISDN.

The logic behind this asymmetrical structure is based on the applications most likely to be provisioned to the residential and SOHO markets, namely video on demand and Internet access. These applications require only text-based queries to be initiated from the subscriber to the service provider.

In other words, the majority of traffic to residential or SOHO subscribers, be it video, file downloads, or applet downloads, flows in one direction. Therefore, bandwidth for these applications is allocated asymmetrically in order to enable overlapping use of the higher frequencies available. However, this asymmetrical apportioning of bandwidth also corresponds to data flows in most client/server applications and particularly Intranet applications. Hence, ADSL also proves to be quite well suited as an access technology for business applications in small, medium, and even enterprise networks.

*Speeds and Feeds for ADSL* — ADSL, as presently standardized by ANSI (American National Standards Institute), is defined as having seven transport classes: four classes based on multiples of T-1 (1.5 Mb/s) downstream bandwidth and three classes based on multiples of E-1 (2.0 Mb/s) downstream bandwidth. Each class specifies a *maximum* possible bandwidth, both downstream and upstream, under a given set of variables such as loop length, wire gauge, and line condition. Classes 1 and 2M1 support the maximum downstream/upstream bandwidth under the best conditions, while classes 4 and 2M3 represent the maximum downstream/upstream bandwidth under the worst conditions. The following charts show the maximum bandwidth possible for each transport class.

In addition to these standardized bandwidth specifications, progress in DSP chipsets has enabled ADSL modems to achieve even faster speeds both upstream and downstream. The fastest speeds announced to date are 12 Mb/s and 2 Mb/s for downstream and upstream speeds, respectively. Needless

| Transport class | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Maximum capacity for downstream simplex channels | 6.144 Mb/s | 4.608 Mb/s | 3.072 Mb/s | 1.536 Mb/s |
| Maximum capacity for upstream duplex channels | 640 kb/s (576 kb/s of usable bandwidth) | 608 kb/s (544 kb/s of usable bandwidth) | 608 kb/s (544 kb/s of usable bandwidth) | 176 kb/s (160 kb/s of usable bandwidth) |
| Control channel (included in the above maximum for the upstream duplex channels) | 64 kb/s | 64 kb/s | 64 kb/s | 16 kb/s |
| POTS channel | 64 kb/s | 64 kb/s | 64 kb/s | 64 kb/s |

Table 1. *Transport classes for T-1-based downstream multiples.*

to say, ADSL features a very large number of speed options within a single technology. Nevertheless, ADSL seems to hold the highest potential in the xDSL family to be able to offer cheap, broadband access to both the home and the office in the near term.

## Other xDSL Flavors

*Rate-Adaptive DSL* — RADSL technology is a subset of ADSL that automatically adjusts line speed based on a series of initial tests that determine the maximum speed possible on a particular line. As one can see from Tables 1 and 2, ADSL speeds can vary greatly based on a number of conditions. In areas where there is a large variance in the length of the local loop (distance from the subscriber to the CO), the gauge of the wire, and the condition of the line, it becomes difficult to determine what speeds should be provisioned over each line. Fluctuating conditions such as weather further act to change the maximum possible throughput on a given line. Since RADSL accommodates the maximum speed available across a particular line, much of the effort and/or guesswork can be taken out of provisioning ADSL.

*Symmetric DSL* — As expected, SDSL provides the same amount of bandwidth upstream as downstream. The price paid for maintaining bandwidth symmetry is lower aggregate bandwidth. At this point, systems operating at 384 kb/s, 768 kb/s, 1.5 Mb/s (T-1), and 2 Mbs (E-1) are available. For this reason, SDSL is not considered a contender in the effort to provide low-cost broadband applications to the residential and SOHO markets. However, most technologies in use today for transmission over the wide area are symmetric, such as time-division multiplexing (TDM) and frame relay. Since xDSL operates at the physical layer of the Open Systems Interconnection (OSI) networking model, SDSL can be used as the underlying transmission scheme for traditional network technologies and services.

The advantage of transporting, for example, frame relay traffic over an SDSL link is cost. Frame relay service or a leased line could be provisioned over a single pair of telephone wires rather than multiple wires or even fiber optic cable. This has the potential of greatly reducing the cost of provisioning existing services that applications demand today. In the case of frame relay, the demand is expected to continue to increase for years to come.

SDSL's symmetric transmission scheme is also optimized for some emerging applications. Isochronous applications, such as video conferencing, have the same bandwidth requirements upstream as downstream. SDSL is also well suited to a peer-to-peer Internet model where Web sites are very highly distributed (i.e., a Web site in every home). However, the current trends indicate that, while everyone may eventually have their own Web site, today they are collocated on centralized servers, thus preserving the asymmetric traffic model. As for video conferencing, while it has a very strong business case, it remains to be seen whether this application will become a dominant form of personal communication in the near term.

*Very-High Rate DSL* — VDSL is essentially the same as ADSL. Like ADSL, VDSL is an asymmetrical transmission scheme; however, VDSL is designed for much higher transmission rates (up to 30 to 51 Mb/s) than ADSL over extremely short distances (500 to 1000 ft). For this reason VDSL is seen by some people as a much more futuristic technology than the other xDSL technologies, becoming appropriate only when applications begin to demand that kind of bandwidth and used in conjunction with fiber to the curb (FTTC) deployment. In addition, VDSL's severe distance limitation precludes it from being implemented in all but the densest environments.

Despite these constraints, there are situations in which VDSL deployment could be justified today. Where dense access environments exist, such as large office buildings or business parks that typically have a CO located on or very near the premises, VDSL could be used to provide lower-cost integrated access or LAN-to-LAN connectivity across a broadband network such as ATM, synchronous optical network (SONET), or synchronous digital hierarchy (SDH). Also, as the fiber plant moves closer to the curb, VDSL will be increasingly utilized to support residential broadband applications.

*High-Bit-Rate DSL* — HDSL is the most widely deployed xDSL technology and has been commercially available for a number of years. Unlike the other xDSL technologies, HDSL uses two pairs of copper cable rather than one and does not carry POTS. Most HDSL implementations provide either 1.5 or 2 Mb/s of symmetrical bandwidth up to 12,000 ft from the CO. These speeds conform to T-1 and E-1 standards, respectively; therefore, HDSL's primary application to date has been the provisioning of T-1/E-1 leased lines in areas that have a high density of business customers (e.g., office parks) and a collocated CO.

HDSL has been attractive in the T-1/E-1 space because it greatly reduces the cost of traditional T-1/E-1 provisioning by eliminating the need for repeaters, loop conditioning, or pair selection. HDSL enjoys a relatively large installed base for this application and, to a certain extent, has been responsible for the substantial decrease in leased line costs seen over the last few years. Nevertheless, in order to compete successfully with SDSL technology in provisioning traditional data services, HDSL needs to develop and expand its distance and bandwidth capacities. Otherwise, SDSL, requiring only a single copper pair for transmission, will emerge as the superior solution.

## xDSL vs. Cable Modems

At this point, cable modems, designed to provide multimegabit bandwidth over existing CATV networks, are viewed as xDSL's primary competitor in the residential access market. However, data services based on CATV's coaxial cable network infrastructure possess a number of shortcomings relative to xDSL.

*Lack of Penetration in Commercial Areas* — While demand for broadband access will certainly rise in the residential market within the next several years, such demand already exists today among corporate customers. However, CATV networks are primarily deployed in residential rather than commercial zoned areas. This lack of infrastructure means that cable companies must install a great deal of coaxial cable into office parks and other areas with a high density of business users. This type of infrastructural investment may simply not be feasible for most cable companies, particularly with their traditionally high debt-to-equity ratios.

| Transport class | 2M1 | 2M2 | 2M3 |
|---|---|---|---|
| Downstream simplex channels | 6.144 Mb/s | 4.096 Mb/s | 2.048 Mbs |
| Upstream duplex channels | 640 kb/s | 608 kb/s | 176 kb/s |
| Control channel | 64 kb/s | 64 kb/s | 16 kb/s |
| POTS channel | 64 kb/s | 64 kb/s | 64 kb/s |

Table 2. *Transport classes for E-1-based downstream multiples.*

*No CATV Infrastructure Outside North America* — CATV is a uniquely North American phenomenon. While there are some exceptions like the Netherlands, there is no significant infrastructure of coaxial cable in Europe or the Pacific Rim, which are the two markets outside the United States and Canada looking to provide residential broadband service in the near future. Therefore, in these areas xDSL will be the technology of choice by default. The addition of international demand will serve to push the cost curves for xDSL modems and other access products down faster than those of cable modems, which, as we have seen in other technology areas, serves to further stimulate demand.

*Security* — Because of the bus architecture of CATV networks, security is a potentially damning weak point, particularly for business applications or on-line commerce. By tapping into the cable at any point in the service area, an individual would able to "see" transmissions to or from a specific user and capture packets transmitted to or from that user. Of course, while encryption technology may prevent the individual hacker from actually reading those packets, an organization with the proper resources may not be so constrained.

Effective security measures rely on multiple layers of protection including encryption, passwords/firewalls, as well as physical barriers to unauthorized access. Since each link in an xDSL service area is carried over a discrete pair of wires, the intruder would have to physically determine which pairs to tap in order to target a specific user. While certainly not impossible, the added time and effort necessary to do so in an xDSL service area are an important layer in overall protection against unauthorized access.

*Network Management* — Cable TV companies have been in the business of delivering television over coaxial cable, not that of providing network services. For this reason, the CATV companies are woefully unprepared to handle the extensive network management issues that arise in delivering data services. Not only do they lack a physical infrastructure that lends itself to management, they have little experience in the area altogether. Again, many cable companies will be hard pressed to make the investments necessary to develop proper network management systems, as well as build an organization knowledgeable in network management.

*The Fatal Flaw — Shared Bandwidth Access* — Perhaps the greatest single shortcoming to broadband services deployed over CATV networks is the fact that these networks are based on a shared bandwidth architecture. While it is true that cable modems can provide more raw bandwidth than xDSL technologies (10 Mb/s to 51 Mb/s), this bandwidth must be shared by all the users in the service area. This means that each time a subscriber is added in a given service area, the bandwidth available to every user in that service area is decreased.

For example, let us assume that a particular service area has 100 subscribers to a 30 Mb/s network service based on cable modem technology. If 30 of those users are accessing the network at a given time, then, effectively, each user has access to only 1 Mb/s. In addition to effecting a marginal decrease in bandwidth per user, this structure also places the service provider in the odd position of having to reduce the subscription price for all users each time a new user signs up in a given service area; otherwise, all users in the service area must pay the same amount for increasingly diminished bandwidth.

On the other hand, bandwidth on a xDSL link belongs solely to the service subscriber. Therefore, assuming there will be multiple users in a given service area, a service based on xDSL technology provides far more bandwidth per user than a service based on cable modem technology. Moreover, when a user subscribes to an xDSL service, that user is guaranteed a certain amount of bandwidth. Not only is this configuration more attractive to the subscriber, it also makes instituting a "cost per unit bandwidth" pricing model a straightforward process.

## The Evolution of xDSL

Still early in its technology life cycle, xDSL continues to advance rapidly. Gains are being made in faster bit rates, further reach, lower power requirements, alternative configurations, and lower costs. Meanwhile, the standards work progresses at a furious pace and interoperability issues are beginning to surface.

## xDSL Price / Performance

A price/performance analysis of xDSL-based solutions vis-à-vis other broadband access solutions would not be complete unless it included the infrastructural and organizational investments necessary in order to implement each technology. Clearly, one of the critical and exciting aspects of xDSL is the prospect of service providers provisioning broadband networking solutions over the existing infrastructure of copper telephone lines.

With regard to the residential market, as we have mentioned, solutions based on an HFC architecture utilizing cable modems will require substantial investment in time and money before the level of penetration is sufficient to justify service deployment. The most optimistic estimates calculate that it will require at least eight years before HFC solutions can be deployed in numbers sufficiently high that the services they deliver begin to turn a profit. Even the eight-year estimate carries several contingencies: the HFC infrastructure is optimally deployed, multiple services are successfully delivered over HFC and sufficiently attractive to the consumer, and the difficulties with a shared bus architecture discussed earlier are ameliorated. Given the long time line involved and the slim margin for error, HFC deployment will be a difficult order to fill for CATV companies or those carriers committed to HFC.

As for the commercial market, it seems that cable modems

| Number of nodes connected to one CO | Bandwidth/node | Cost of connection | Connection cost/ bandwidth ($/Mb/s) |
|---|---|---|---|
| 1 | 6 Mb/s | $2300 | $383 |
| 5 | 6 Mb/s | $2050 | $342 |
| 25 | 6 Mb/s | $1750 | $292 |
| 225 | 6 Mb/s | $1300 | $216 |

■ Table 3. *ADSL connection cost per unit of bandwidth.*

face an even more daunting challenge since the coaxial cable infrastructure (much less an infrastructure that can support broadband applications) presently reaches few office buildings and business parks. Suffice it to say, in terms of return on investment, xDSL technologies hold a substantial advantage over cable modem technologies as broadband services are deployed on a large scale.

One of the advantages that cable modems have claimed over xDSL technologies, ADSL in particular, is lower cost at the endpoints. Due to the fact that cable modems are slightly farther ahead on the demand curve, there is a sizable discrepancy between the cost of ADSL modems and cable modems at the moment. However, as ADSL modem production begins to ramp up, this discrepancy is expected to all but disappear.

Nevertheless, for the sake of comparison, we have created a price/performance analysis between cable modems and ADSL modems based on average street prices for each at the present time. As is standard practice in the networking industry, this price/performance comparison is made on the basis of cost per unit of bandwidth (in this case, dollars per megabits per second). Looking at the price/performance comparisons in Tables 3 and 4, it is again clear that the shared bandwidth model of cable modems prevents this solution from competing favorably with xDSL on a dollars per megabits per second basis.

For the end-user customer, one of the most compelling applications for broadband access technologies is Internet access. Table 5 shows the cost per unit bandwidth for the customer. Various access technologies are compared.

As mentioned, the above comparisons reflect the pricing of ADSL modems as they stand at this very moment. Of course, the prices of ADSL modems will certainly decrease substantially over the next year and may even fall by a whole order of magnitude by the year 2002. The falling prices of ADSL modems will result in a corresponding decrease in the price of ADSL services. Furthermore, not only are prices likely to fall substantially, but performance is also expected to rise. For example, this year an ADSL chipset supporting 12 Mb/s has been successfully tested, and for short distances VDSL modems will support speeds between 30 Mb/s and 50 Mb/s (Figs. 1 and 2).

## xDSL Standards

As is the case for many physical-layer technologies, ANSI, the European Telecommunications Standards Institute (ETSI), and now the International Telecommunications Union — Telecommunications Standardization Sector (ITU-T) are actively involved in creating standards for xDSL. Additionally, since ADSL and VDSL, in particular, provide the foundation of a platform for new residential broadband services, additional organizations are involved in the specification work for ADSL and VDSL. These organizations include the ATM Forum, the ADSL Forum, the Telecommunications Industry Association (TIA), and the Digital Audio Visual Council (DAVIC). These organizations are creating interoperability specifications that span end-to-end residential broadband systems. While the ATM Forum covers only ATM over ADSL and VDSL, the other organizations also produce specifications for IP/packet mode and bit-synchronous mode over ADSL and VDSL end systems.

*ANSI, ETSI, and ITU-T* — The locus of xDSL standardization work to date has been in ANSI T1E1.4. T1E1.4 is currently working on all the xDSL technologies: HDSL (SDSL), ADSL (RADSL), and VDSL. Work on HDSL started in late 1989. ADSL work started in 1992. Work is progressing on the following: a standard for HDSL2 (a second generation for single-pair HDSL), Issue 2 of two-pair HDSL, Issue 2 of ADSL, carrierless amplitude phase modulation (CAP)-based RADSL, and VDSL.

ETSI TM6 has also been a major contributor to the xDSL standardization work. ETSI xDSL work began in 1992 and currently covers all the xDSL technologies. TM6 decisions are being made with consideration of T1E1.4 work.

Recently, the ITU-T, in planning for the next plenary, assigned a new question to Study Group (SG) 15, Access Network Transport. The question calls for international standardization for DCEs providing high-speed digital access services, including modulation techniques and procedures for HDSL, ADSL, and VDSL. While the core xDSL work will begin in SG15 in 1997, there will be some related items in Study Group 13 as well.

*The ADSL Forum, DAVIC, and the ATM Forum* — Unlike the standards bodies discussed above, these fora and consortia have established a record pace for publishing specifications. Focusing on the end-to-end systems issues for packet, ATM, or bit-synchronous services over ADSL/RADSL and VDSL transport, these organizations are actively liaising with each other as well as T1E1.4 and TM6.

Formed in late 1994, the ADSL Forum is currently close to publishing Issue 1 documents on packet mode and ATM over ADSL. There appears to be consensus in this Forum to take on VDSL systems issues going forward, as they interpret the A in ADSL Forum to mean "any" xDSL.

Formed in late 1991, the ATM Forum has two working groups relevant to ADSL specifications. The Physical Layer (PHY) Working Group covers all physical-medium-dependent (PMD) sublayers and transmission convergence (TC) sublayers for ATM. Although the ATM Forum has yet to work on an ADSL or VDSL PMD, contributions have been heard on

| Number of nodes connected to one headend* | Bandwidth/node | Cost of connection | Connection cost/bandwidth ($/Mb/s) |
|---|---|---|---|
| 1 | 10 Mb/s | $700 | $70 |
| 5 | 2 Mb/s | $650 | $325 |
| 25 | 0.4 Mb/s | $600 | $1500 |
| 225 | 0.044 Mb/s | $450 | $10,227 |

* Most plans call for between 50 and 100 nodes to be connected to a single headend.

■ Table 4. *Cable modem connection cost per unit of bandwidth.*

| Access technology | Number of nodes connected to one CO/headend | Bandwidth per node, — downstream/ upstream | Monthly cost of Internet access | Cost of bandwidth provided ($/kb/s) |
|---|---|---|---|---|
| ADSL modem | 225 | 6 Mb/s/.74 Mb/s | $90 | $.015/$1.22 |
| 28.8 kb/s modem | 225 | 0.0288 Mb/s | $11 | $3.82 |
| ISDN BRI | 225 | 0.128 Mb/s | $60 | $4.69 |
| T-1 leased line | 225 | 1.5 Mb/s | $1,200 | $7.74 |
| Cable modem | 1 | 10 Mb/s/ 1 Mb/s | $50 | $.05/$.5 |
| Cable modem | 5 | 2 Mb/s/.2 Mb/s | $50 | $.25/$2.50 |
| Cable modem | 25 | .4 Mb/s/.04 Mb/s | $50 | $1.25/$12.50 |
| Cable modem | 225 | .044 Mb/s/ .004 Mb/s | $50 | $11.36/$113.64 |

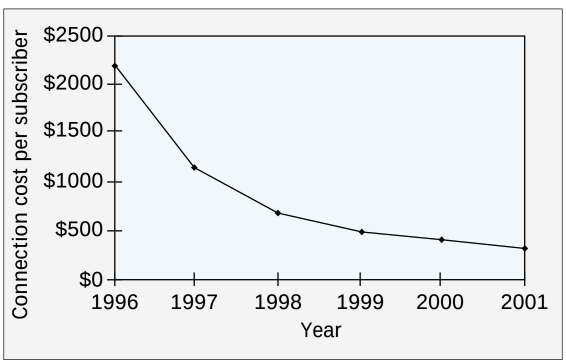
■ Table 5. *Internet access technologies measured by cost-of-service/unit bandwidth.*

transmission convergence (TC)-layer issues for both ADSL and VDSL. The end-to-end system aspects for ATM over ADSL and VDSL are discussed in the Residential Broadband (RBB) Working Group. This group meets jointly with PHY on ADSL and VDSL physical layer issues and is exchanging liaisons with nearly all the other organizations mentioned in this section. Recently the RBB group asked the ADSL Forum for a joint work session to further work on the ADSL Forum's specification for ATM over ADSL and subsequently ATM over VDSL.

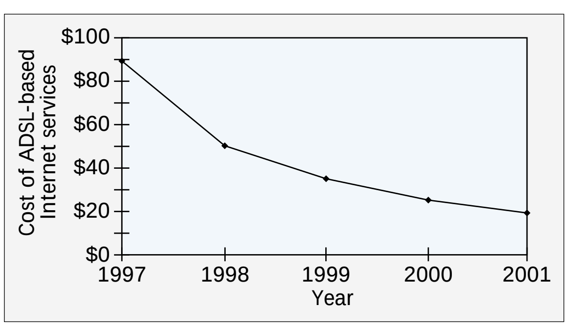
DAVIC is also nearing publication of an ADSL ATM mapping specification as part of DAVIC 1.2. This specification includes definition of an ATM TC layer for ADSL. The DAVIC specification will reference the ADSL Forum document if it is done in time.

Other organizations working on related items include IEEE P.1007, the TIA TR41.5 (specification for a network gateway), and IEEE 802.14 (for VDSL).

*DMT vs. CAP* — There has been much ballyhoo regarding the line code standardization efforts for ADSL. DMT (discrete multitone) and CAP were the two primary candidates for the ADSL line code. Three years ago, in a bake-off that at best compared apples to oranges, DMT was the perceived performance winner. In actuality, the CAP product was tuned to support simultaneous POTS, ISDN, and high-speed data, while the DMT product was tuned to support only high-speed data. The CAP products, although temporarily losing the line code debate, are now predominate in the marketplace while DMT products are only beginning to emerge on the scene. The CAP technology is in its third generation of chips with several years of experience in trial service deployment. The industry is now dealing with a scenario reminiscent of Transmission Control Protocol (TCP) vs. OSI. CAP, similar to TCP, is four to five times less complex, with better price, performance, and power characteristics, than DMT. CAP's market lead gives it more momentum to stay ahead of the price/performance curve. DMT, similar to OSI, is a good theoretical solution, yet difficult to bring to market. In recognition of the current state of the ADSL market, work is now underway for a CAP-based RADSL standard in T1E1. Interestingly enough, several DMT companies are currently proponents of CAP as the line code method for VDSL.




■ Figure 1. *Per subscriber ADSL deployment cost forecast.*




■ Figure 2. *ADSL-based Internet service cost forecast.*

### *xDSL Interoperability*

xDSL is neither ISDN nor ATM. xDSL interoperability is not end-to-end compatibility; that is, neither end-user-to-end-user nor end-user-to-switching-system . xDSL end-to-end interoperability is within the context of a short-span line driver. For today's deployment purposes, interoperability is only needed over the short span from premises to CO. Today, only CAP products are interoperable. The DMT product vendors are beginning to work together to plan for future interoperability of their products, which will not happen for at least two years.

Given the almost frenzied pace of the standards work and the rapid pace of technology innovation in the xDSL space, we are witnessing an extremely strong technology push.

## *The Business Case for xDSL*

Several factors are key in developing the business case for deploying xDSL. In particular, for the residential broadband market, the business case for ADSL is based on considering the following factors.

*New Revenue* — Generation from value-added services such as Internet access and VOD. Given the eroding POTS market, where price competition is high and the threat of alternative services such as voice over the Internet is increasing, ADSL gives service providers the option to skim the cream by offering higher-priced, higher-margin residential broadband services.

*Infrastructure Deployment/Upgrade Costs* — Utilizing the existing copper twisted pair and not requiring any terminal adapters or special client or host software, provisioning simply requires the addition of two ADSL modems per subscriber line.

*Incremental Deployment Options* — ADSL deployment does not require groups of subscribers to be enabled at one time or an entire switch to be upgraded. Each and every subscriber line can be made ADSL-ready independently.

*Easy Migration Path* — If higher-speed services are needed at a particular subscriber location, the ADSL equipment can be replaced by VDSL equipment (and perhaps a longer fiber run). The ADSL equipment can then be reused at another subscriber location.

*Service Provisioning Time Improvements* — ADSL installations are essentially "plug and play" compared to other infrastructures in support of residential broadband services.

> *xDSL applications can be roughly divided into residential user and corporate user categories. Over time, as work at home and on-line commerce become more prevalent, the distinction between residential and corporate users will blur.*

*Network "Hold Times" Improvements* — Internet calls are tying up network resources for hours. The POTS network, originally designed for voice calls averaging only minutes in duration, is becoming increasingly taxed. ADSL allows the telephone companies to free these resources by redirecting the ADSL calls at the CO to an auxiliary high-speed data network.

*Network Switch Port and Loop Utilization Improvements* — SOHO workers, like myself, can replace their two- to four-line offices (up to one each for office voice calls, office fax calls, Internet/Intranet calls, and personal calls) with one-line ADSL service.

*Minimizing Lost Rrevenues Due to the Competitive Threat* — In addition to the threat from CATV companies, the deregulated telephone company environment allows for competition in the local loop. Who will be the first to deploy ADSL and capture the new revenue stream?

With these many factors contributing to building a positive business case, we will witness strong market pull from both end users and service providers for ADSL.

## xDSL Broadband Services

### Applications

xDSL applications can be roughly divided into residential and corporate user categories. Over time, in many cases, as work at home and on-line commerce become more prevalent, the distinction between residential and corporate users will blur.

*Residential User Applications —*
Internet Access — As everyone knows, the advent of the World Wide Web has resulted in the phenomenal growth of the Internet over the past two years. However, the infrastructure of the Internet has yet to be optimized for transferring the rich graphics common on today's Web sites. The majority of users accessing the Web do so via the public switched telephone network (PSTN) and 14.4 kb/s or 28.8 kb/s modems. In addition to the bandwidth limitations of analog access, the switches that make up the PSTN are optimized for short connections that characterize telephone calls rather than the calls of several hours typical of Internet sessions. This problem puts a great deal of strain on the PSTN and potentially threatens the low, fixed pricing model of Internet access.

In addition to expanding bandwidth for Internet access by a factor of over 100, service providers are looking to xDSL as a way to keep Internet traffic off the PSTN. Although there are various network models, the idea is to shunt traffic from xDSL connections off the local loop directly onto the Internet. POTS splitters at both ends of the loop would keep normal telephony service intact.

Another aspect of the Web that makes xDSL a compelling access solution is the asymmetric nature of Web-based data communications. In most cases, the only upstream traffic users send to the service provider are universal resource locators (URLs), very short text messages that allow the user to move from Web page to Web page. The majority of Web traffic flows downstream in the form of graphic-intensive Web pages, moderate to large text files, audio files, and even video clips downloaded by the user from Web servers. Clearly, ADSL's asymmetric apportioning of bandwidth is optimized for Web access.

TV/Video on Demand — ADSL was originally targeted as a way for telephone companies to compete with CATV companies by delivering TV programming and VOD services to residential customers over ordinary telephone wires. While VOD did not prove to be the killer application everyone had hoped for, bundled with Internet access, the ROI (return on investment) analysis looks much more compelling. Furthermore, most countries outside North America do have very small CATV network infrastructures. By delivering TV programming and VOD services bundled with other services, including Internet access and POTS service, ADSL can enable the PTTs of many countries to become a one-stop shop for communications and content.

*Corporate User Applications —*
Leased Line Provisioning — Perhaps the most popular xDSL application to date is to greatly reduce the cost of provisioning T-1 or E-1 leased lines from the CO to the customer's site. HDSL has been used in this way for the last few years and has achieved a great deal success. In the following year, it is expected that SDSL will replace HDSL in this application since the same performance and reach characteristics can be achieved with only one pair of wires (SDSL) as opposed to two (HDSL).

xDSL technologies, SDSL in particular, will also give non-telephone-company service providers — such as VANs (value-added networks), ISPs (Internet service providers), and CAPs (competitive access providers) — the ability to provision T-1 and E-1 leased lines themselves, given they have access to the local loop. If these service providers are able to lease "dark copper" from a particular telephone company's CO to the customer, as well as lease space for their switching equipment at the CO, they would be able to provision T-1 and E-1 leased lines to the customer at very low cost using xDSL. It should be noted that, in the United States, the recently passed telecommunications reform legislation has been written to allow non-telephone-company service providers access to the local loop and the CO.

Interestingly, this situation could give rise to the provisioning of E-1 leased lines in the U.S. market, since SDSL supports 2 Mb/s and TDM switches, and multiplexers from most manufacturers can support E-1 interfaces. Using SDSL as the underlying transport mechanism, there is little reason for the service provider not to provision a leased line offering 30 percent more bandwidth for the same price. Nontarriffed E-1 provisioning could be one way for alternative access providers to compete against and differentiate themselves from telephone companies.

> *Since it can be deployed over an existing telephone line, xDSL represents very close to an order of magnitude of cost savings when compared to provisioning a T-1 for frame relay access.*

**LAN-to-LAN Interconnect** — In the legacy host-terminal network environment, wide-area bandwidth requirements are modest, requiring only the transmission of keystrokes and textual screen updates. However, as client/server applications continue to take on mission-critical tasks of the enterprise and become increasingly bandwidth-intensive, cost-effective broadband technologies become extremely attractive for linking LANs throughout the enterprise network.

It is the strength of the demand for LAN-to-LAN connectivity solutions that has pushed the frame relay services market to above 100 percent average annual growth over the past three years. xDSL is expected to enjoy similar growth over the next several years, pushed by the demand to connect LANs at broadband speeds for a fraction of the cost of leased lines. While ADSL is certainly a viable and, in some instances, very attractive technology for LAN-to-LAN connectivity, initially symmetric technologies such as HDSL and SDSL will be most popular in this application.

**Frame Relay Provisioning** — In many of the situations where xDSL is used to connect LANs, frame relay can be used as the transport mechanism in order to keep the present network architecture intact, maintain the current network management applications, and ease migration overall. However, provisioning frame relay services over xDSL has applicability in and of itself for uses outside LAN-to-LAN connectivity, such as integrating legacy data transport and voice transport within the enterprise. This latter application is attracting interest in international markets because customers can take advantage of the relatively distance-nsensitive pricing that characterizes frame relay offerings. Essentially, all the applications available using frame relay are available when frame relay is run over xDSL. The advantages of using xDSL as the underlying transport mechanism are:

- Cost — Since it can be deployed over an existing telephone line, xDSL represents very close to an order of magnitude of cost savings when compared to provisioning a T-1 for frame relay access.
- Increased bandwidth — At this point, the vast majority of frame relay services are limited to T-1 speeds. Using ADSL as a transport technology, frame relay could achieve speeds of 6 Mb/s downstream today.

These costs and bandwidth advantages may enable frame relay over xDSL to be used in ROBO and possibly even SOHO residential environments.

**Intranet Access** — While Internet access will be a critical market for xDSL going forward, Intranet access may be more important in the near term. Intranets are private networks that utilize Web-based architectural components (Web servers, browsers, horizontal linkage, etc.) and Web protocols/languages (TCP/IP, HTML, Java, etc.) to deliver enterprise-wide applications. Many organizations are moving to an Intranet architecture as a way to amalgamate multiple applications, systems, and platforms under the umbrella of a single network architecture. However, Intranet access is at least as, if not more, bandwidth-intensive than Internet access. Therefore, ADSL is ideal for enabling organizations to connect telecommuters to the company's Intranet at speeds similar to those they are used to on the corporate LAN. In addition, ADSL can be used to give cheap, high-speed Intranet access to remote/branch offices, thus avoiding the expense of installing and maintaining proxy Web servers on site at these peripheral offices.

## *Trials*

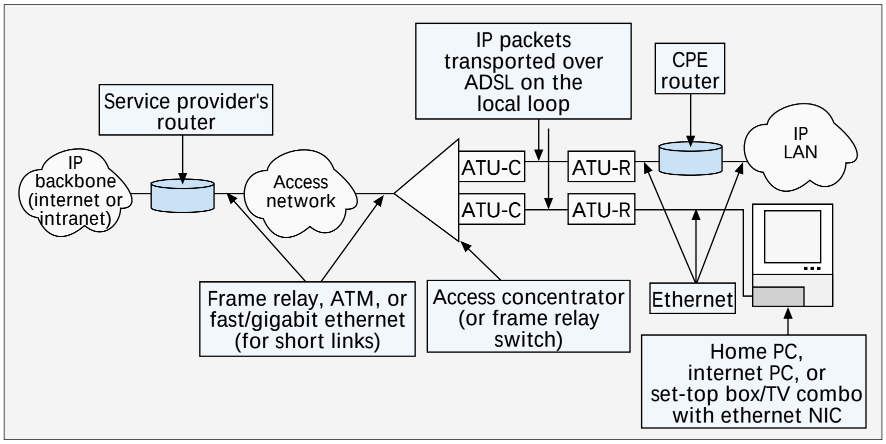
The following is an overview of the some of the many xDSL trials presently being conducted:

*GTE ADSL Trial in Redmond, Washington* — GTE has recently launched a six-month trial for ADSL service in Redmond, Washington. While Microsoft will be the primary subscriber, the University of Washington and several local businesses will also participate. Several applications using the ADSL service will be deployed, including Internet access, remote access for people working at home, Web server egress, as well as possible video conferencing services over SDSL. Initially, the ADSL services will provide 1.5 Mb/s of bandwidth downstream and 64 kb/s upstream. Later, the service will also offer speeds of 6 Mb/s downstream and 640 kb/s upstream.

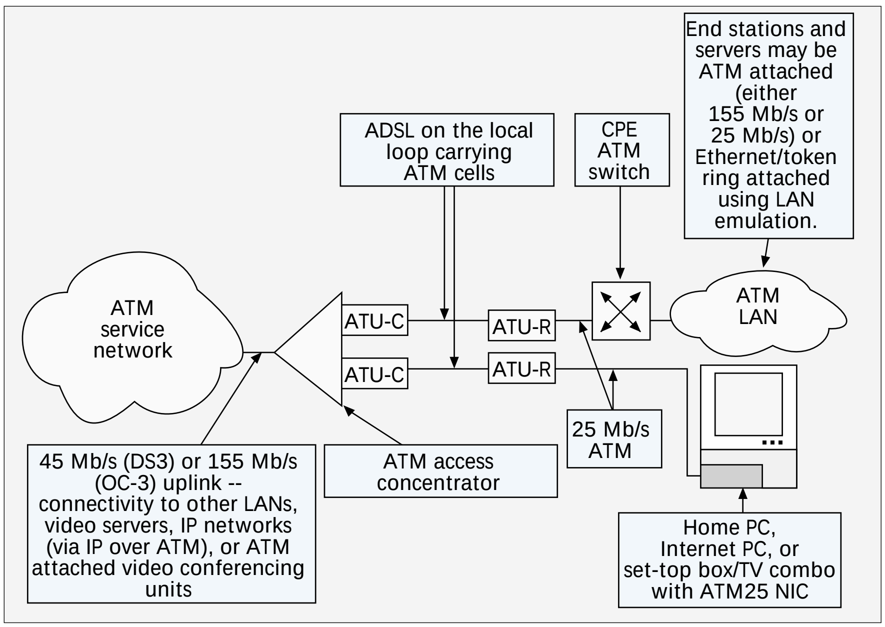
*U.S. West ADSL Trials in Boulder and Minneapolis / St. Paul* — This trail began in April 1996 and is available solely for its own employees. Both ADSL (1.5 Mb/s/64 kb/s) and HDSL (740 kb/s) services are being tested for Internet access and remote access of corporate LANs by users based at home. The subsequent phase of this trial will be to open up the service to select non-U.S. West employees who will also use the service for Internet access and accessing their own corporate LANs. U.S. West foresees commercial ADSL services beginning to roll out in certain areas by the end of 1997.

*UUNet ADSL Trial in Toronto* — An ISP, UUNet Canada, is presently testing a 1.5 Mb/s/64 kb/s ADSL service for a single corporate customer with multiple remote sites. Internet and Intranet access are the primary applications being evaluated. This trial began in June 1996 and is significant in that is one of the first trails conducted by an ISP.

*Swiss Telecom ADSL Trial* — Swiss Telecom is presently conducting a trial for multiple services delivered over ADSL to approximately 200 households. These services include VOD, "edutainment" programming, and on-line shopping. The ADSL service in this trial provides 2 Mb/s of bandwidth downstream and 9.6 kb/s upstream.




■ Figure 3. *IP model.*




■ Figure 4. *End-to-end ATM model.*

## *Network Models*

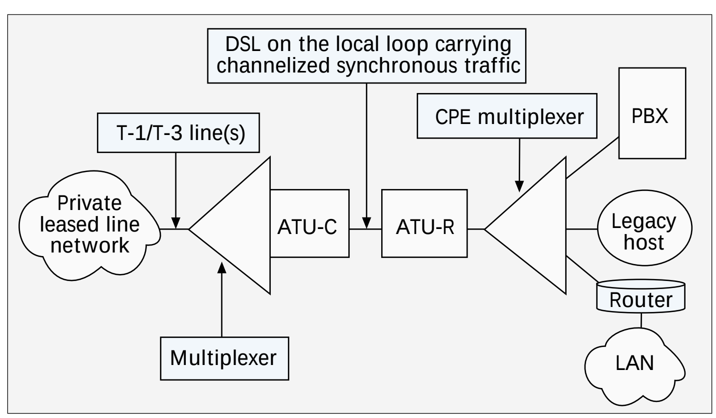
Since xDSL is a point-to-point transmission technology functioning primarily at the physical layer, it can support a variety of networking protocols. Most service providers are looking to xDSL and ADSL in particular to serve as the access technology component in a broadband network architecture that will support multiple services and applications. Depending on the technological or strategic inclination of the specific service provider, the application and/or services delivered, and the market (corporate or residential) for those applications and services, the nature of this new broadband architecture can vary greatly.

Because the subject of broadband network architecture delves into issues beyond the scope of this article, we will only describe three basic architectural alternatives for xDSL deployment. *It is important to understand that, at this stage, there is little consensus regarding which network architecture or model is most appropriate to support xDSL as an access technology, and there are several permutations of the basic models outlined here. The ATU-C is an ADSL terminal unit for the CO. The ATU-R is an ADSL terminal unit for the remote site* (Fig. 3).

Using ADSL as a transport mechanism for IP traffic is the obvious choice for Internet access applications. The model depicted is only one of many possible versions of this model. In addition, the IP model can also serve other applications as well such as Intranet access, LAN-to-LAN connectivity, and others. While several intermediary protocols, such as frame relay or ATM, could be used between IP and ADSL, the ADSL Forum has also specified transporting IP packets directly over ADSL without the use of an intervening protocol. This scenario can be seen as similar to running IP directly over a physical-layer transport mechanism such as SONET. In this case, a router or a device with integrated routing would be necessary at the CO, rather than an access concentrator or switch operating only at layer two.

Depicted above are both corporate applications and residential applications. In the residential case, a personal computer (PC), or perhaps an Internet TV, is located on the ATU-R side of the ADSL link (the ATU-R may reside in the PC's bus or be connected to the PC via Ethernet), and access to the IP network is established via a point-to-point protocol (PPP)-over-ADSL connection (Fig. 3).

Due to the fact that ADSL provides a dedicated connection of relatively high bandwidth, it may also be used to extend the ATM network, and therefore the quality of service (QoS) properties of ATM, all the way to the residential or corporate desktop. The ADSL Forum has specified how ATM cells are transported over ADSL. Essentially, the ATM user-to-network interface (UNI) is tunneled through an ADSL link. By having desktop applications talk directly to the ATM network, bandwidth can be reserved (and guaranteed) end-to-end across the network. This facilitates the deployment of isochronous, delay-sensitive applications such as voice, video conferencing, and so on. The next release of Windows 95 will include an API (application programming interface), Winsock 2, which will allow applications to request QoS from the ATM network.




■ Figure 5. *Circuit switched model.*

However, ATM, particularly ATM operating at speeds below 25 Mb/s, exacts a fairly high overhead, and therefore may not be justified by many applications that do not have stringent QoS requirements or are able to function with the nonguaranteed QoS services offered by protocols such as RSVP (Reservation Protocol). In addition, many large organizations that would require ATM service may be better off subscribing to a 45 Mb/s (DS-3) or 155 Mb/s (OC-3) ATM service operating over fiber rather than transporting ATM cells over multiple ADSL links. Finally, to the degree that corporate users or residential users are interested in ATM service for peer-to-peer applications such as video conferencing, the asymmetric apportioning of bandwidth under ADSL would not be optimal. Nonetheless, telephone companies are interested in ATM over ADSL due to the cost savings obtained by not requiring large CO-based cell conversion devices (Fig. 4).

*Unlike some technologies that stall between the lifecycle acceptance phases of early adopter and mass market, the conditions are right for xDSL to advance rapidly to mass market adoption.*

As mentioned earlier, xDSL technologies can be used simply to drastically reduce the cost of leased line provisioning. In this way, xDSL technologies can be smoothly integrated into existing network architectures that are based on private leased lines using TDM technology. In general, this model does not apply to the residential user (Fig. 5).

## Conclusion

The answer to the question posed in the beginning of this article, why xDSL has emerged as the access technology of choice, is based on infrastructure. The xDSL family of technologies provides a wide variety of line driving schemes to accomplish and satisfy different market needs over today's infrastructure. Although xDSL has application in both the corporate and residential environments, within the residential broadband space alone, we have a plethora of possibilities. The market needs are still evolving. There is no single tool to build a house. In the context of xDSL, whether two-pair, single-pair, asymmetric, symmetric, rate-adaptive, or multichannel, digital subscriber loop technologies are all tools to utilize in building a service. xDSL has the flexibility to meet the market challenges.

As we have demonstrated, the xDSL space is characterized by both very strong market pull and strong technology push. Unlike some technologies (e.g., ISDN) that stall between the life cycle acceptance phases of early adopter and mass market, the conditions are right for xDSL to advance rapidly to mass market adoption.

## Additional Reading


[1] ANSI T1.413, "Asymmetric Digital Subscriber Line (ADSL) Metallic Interface."
[2] T1E1.4/96-170, "Draft Interface for a CAP Based RADS; System."
[3] C. Price and R. Shuchat, "ADSL: Technology and Market Assessment," IDC, Oct. 1996.
[4] The Yankee Group, "ADSL after Video-on-Demand: The Telco's Weapon in Internet Access," Aug. 1996.
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## Biographies


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