The Development and Standardization of Asymmetrical Digital Subscriber Line

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ABSTRACT It has been almost a decade since the original proposal of ADSL was brought to the attention of a telecommunication standards body. During that time, the idea of ADSL has been modified and refined to fit market demand, many generations of ADSL chip set have been developed, and numerous trials have been conducted to prove its viability. In this article, the early development and standardization efforts of ADSL are reviewed. This is followed by a discussion of practical issues such as central office network interface and customer premises configuration options. These issues have not been addressed extensively but implied by standards documents. The effect of in-house wiring and recent industry-wide standardization activities are then briefly addressed.

Asymmetrical digital subscriber line (ADSL) is one of a variety of digital subscriber line (DSL) [1] systems built upon the existing twisted-pair telephone subscriber loop plant. DSL is a broadband transmission system utilizing spectrum resources beyond the 3.3 kHz voice channel. In other words, when making a conventional telephone connection, the voice channel is very much defined and, therefore, the signal bandwidth is limited by central office (CO) terminal equipment in terms of switch line cards. That is why the transmission throughput of a voice band modem is capped at approximately 50 kb/s. On the other hand, in contrast to the voiceband modem, the installation of DSL transceivers is also required at the CO end of the telephone loops. Therefore, the deployment of a DSL system demands an initial investment at the COs.

Since there are so many different versions of DSL systems, people have used the name xDSL, where x stands for any version. There are four DSL systems that are closely related to standardization. The first standardized DSL system was called DSL and is the physical layer of the ISDN basic rate access channel [2]. This physical layer is characterized by a transmission throughput of 160 kb/s based on a two bit per quaternary (2B1Q) line code for a coverage of resistance design loops of up to 18,000 ft. Main signal processing techniques involved are decision feedback channel equalization (DFE) and echo cancellation (EC). The second DSL system specified by a technical report from a standards committee is the high-bit-rate digital subscriber line (HDSL) [3]. Deployed in a pair, HDSL is promoted as the repeater-less T1 technology. HDSL is characterized by a transmission throughput of 800 kb/s on each telephone subscriber loop, also based on a 2B1Q line code for coverage of a carrier serving area (CSA). Main signal processing techniques involved are the same as those of the ISDN basic rate access channel, but at five times the processing speed.

The third standardized system is ADSL [4]. Most recently, issue 2 of the standard has been released. The fourth system being developed is the very-high-speed digital subscriber line (VDSL) [5]. It is characterized by downstream (from a CO to a telephone subscriber) transmission throughputs of 13, 26, or 52 Mb/s. Both discrete multitone (DMT) and carrierless amplitude and pulse modulation (CAP) line codes are considered. Concurrently, the standardization of single-pair HDSL (SHDSL) is also underway [6]. SHDSL is designed to deliver T1 transmission throughput over a single twisted-pair telephone loop over the CSA serving range. A coding gain of about 5 dB is necessary to achieve this transmission performance objective. In addition, signal spectral shaping and placement are also carefully engineered for obtaining an optimal performance.

There are also a few other names for DSL systems promoted by individual companies and industry groups. ISDN DSL (IDSL) is a variant application of the ISDN basic rate access channel physical layer technology. Instead of connecting to two 64 kb/s B channels and one 16 kb/s D channel, the whole transmission throughput of an IDSL, 160 kb/s, is linked to a backbone data network with or without traffic concentration. Symmetrical digital subscriber line (SDSL) is a single-pair application of the basic HDSL technology. Depending on the serving distance, the transmission throughput of an SDSL can be lower or higher than the original design objective of 800 kb/s. Rate adaptive digital subscriber line (RADSL) is characterized by the CAP line code with transmission capabilities similar to those of the DMT line code-based standardized ADSL. The transmission throughputs of RADSL vary from a few hundred kilobits per second to a few megabits per second in the downstream direction.

At the time ADSL was developed, the broadband service for the mass residential market was thought to be video on demand. A minimum of T1 transmission throughput was required to deliver a compressed video channel. HDSL is capable of T1 transmission throughput. However, the need for two pairs and the CSA range limitation may prove prohibitive in certain areas where a significant portion of customers are beyond 12,000 ft or where the number of pairs per living unit are less than two. In other words, the objective of ADSL was to cover a serving distance of up to 18,000 ft on a single twisted-pair telephone subscriber loop with a T1 transmission throughput at 1.544 Mb/s. This transmission throughput performance can only be achieved by avoiding the effect of near end crosstalk (NEXT) noise. ADSL avoids the effect of NEXT by allocating signal spectra at opposite directions within different frequency bands: the upstream (from a subscriber to a CO) signal spectrum is located right above the voice band; the downstream signal spectrum is located above that of the upstream.

EARLY DEVELOPMENT OF ADSL

Observing that many services needed greater transmission rates from the CO to the subscriber than in the other direction, Dr. Joseph Lechleider proposed the idea of asymmetrical

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DSLs (ADSL) [7]. Adding asymmetry to a DSL opened a new dimension to be considered with the system configuration. Among the options considered by Lechleider were: 18 kft range, 2B + D full duplex, and 1.544 Mb/s downstream; CSA range, 2B + D full duplex, and 3.088 Mb/s downstream; and 5 kft range, 1.544 Mb/s upstream, and 6.176 Mb/s downstream single-pair as well as a few other dual-pair ADSL options. For the first two options, Lechleider assumed a unilateral downstream channel occupying a frequency band above 75 kHz in addition to DSL. For the third option, Lechleider assumed a unilateral downstream channel occupying a frequency band above 425 kHz in addition to a double baud rate HDSL. The higher transmission throughput of unilateral channels is possible because they are only limited by the effect of far end crosstalk (FEXT).

The capabilities of ADSL are well suited to the concept of a video-on-demand service provided through the existing copper loop plant. The CCITT H.261 recommendation and the ISO Moving Picture Experts Group (MPEG) recommendation both provide full motion video at rates of around 1.3 Mb/s. The video, an audio channel, and associated overhead can be transmitted within a 1.5 Mb/s signal. Users could signal the network, scan archives of programming, and receive video "on demand." For this service, only a low transmission throughput upstream control channel is necessary to send back control signals for interactive commands such as pause, play, and so forth. The capabilities of ADSL are also well suited to applications such as network computing, where software and database records could be stored on network servers and retrieved at a speed equivalent to CD-ROM access, and tele-education, where a specialist can be shared with a large student population through downstream channels, and individual feedback can be provided through upstream channels.

Researchers realized that for residential applications, a POTS service, where the traditional telephone service can be provided whether the ADSL is on or off, was more practical than ISDN service. After sharing ideas among Bellcore, the regional Bell operating companies, and other leading industry and academic DSL proponents, ADSL was proposed as having the traditional duplex POTS channels, occupying the frequency band between 300 Hz to 4 kHz, an upstream control channel of 16–64 kb/s, occupying the frequency band between 10 kHz to 50 kHz, and a downstream channel of 1.544 Mb/s, occupying the frequency band between 100 and 500 kHz.

Under this general ADSL spectrum arrangement, the actual transmission of data can be accomplished with the implementation of different line codes. In additional to numerous computer simulation studies predicting transmission performance corresponding to these line codes, an "Olympic" test of ADSL prototypes was also conducted by Bellcore. The "Olympic" test measurements showed Amati's[1] ADSL prototype in first place, Reliance/Bellcore's ADSL prototype in second place, and AT&T Paradyne's ADSL prototype in third place. The operation of the POTS sharing the same test loop was also verified for Reliance/Bellcore and Amati prototypes. Little disturbance was observed. Amati's ADSL prototype had forward error correction code. Based on these test measurements, DMT line code was selected as the ADSL standard, also based on the fact that Amati's prototype could operate at 6 Mb/s in addition to 1.5 Mb/s.

The standard specification of ADSL, code named T1.413, was first released in 1995 by the ANSI T1E1 committee. Meanwhile, ADSL was also promoted at professional technical conferences and by the formation and activities of the ADSL Forum. ADSL technology has been in technical and market trials since early 1994. The purpose of the technical trial was to verify the performance of ADSL technology in the field. The purpose of the market trial was to obtain user feedback about the technology and its potential applications. Technical trials have established the viability of the ADSL technology. Market trials have likewise indicated strong user interest. Most recently, ADSL has been considered as an ideal vehicle for Internet access and telecommuting applications.

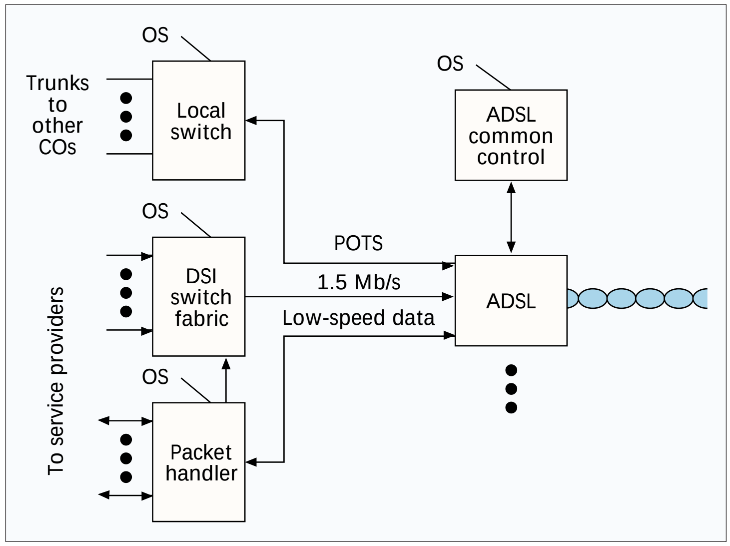

Figure 1. *A switch-based central office ADSL interface.*

Deployment of ADSL Services

Network Interface

Interface to the Digital Hierarchy — ADSL was originally designed mainly for providing video-on-demand services. For this original application, an ATU-C accepts the 1.5 Mb/s signal input and provides the low-speed control channel and the POTS channel. The POTS channel terminates on a conventional local switch. The 1.5 Mb/s stream is provided by switched DS1 services. The low-speed control channel terminates on a packet handler, which in turn communicates with the DS1 switch and the information service provider (ISP) as depicted in Fig. 1 [8].

ADSL can also be used with remote electronics. The POTS service terminates on a conventional plug-in in a digital loop carrier remote terminal. The 1.5 Mb/s signal is carried over a spare DS1 channel on the fiber multiplexer that feeds the remote electronics site. The low-speed data channel terminates on a data channel unit in the remote terminal, or perhaps a number of ADSL low-speed control channels are concentrated first before being transported over a 56 kb/s data channel.

To enable the use of existing data protocols, it is desirable for the low-speed control channel to be full duplex. At least two data formats were considered. The control channel can be implemented with an X.25 protocol, which could run at relatively low speeds, such as 9.6 kb/s. The network transport is widely available for the X.25 protocol. The control channel could also be implemented through an ISDN basic rate "D" channel. ISDN basic rate services are available from most central offices.

Figure 1 includes an ADSL common controller that communicates with a number of ADSL central office units. The central office units in turn communicate with the remote units

[1] *Founded by Prof. J. Cioffi of Stanford University during 1991, Amati was acquired by Texas Instruments Inc. in late 1997.*

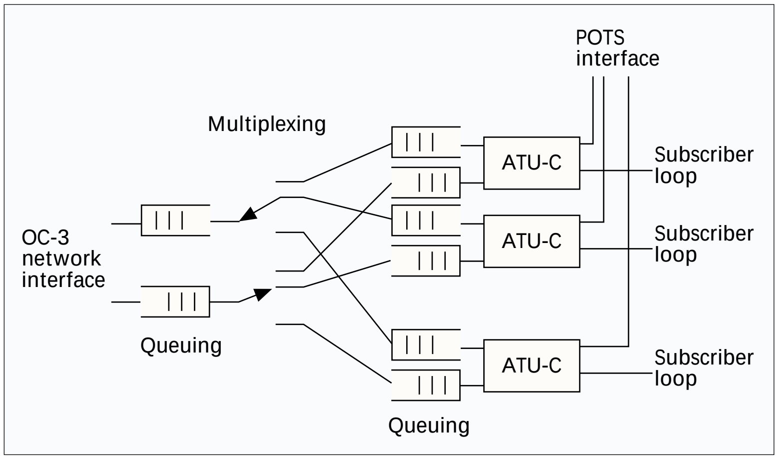

Figure 2. *The general structure of a DSLAM.*

by way of an overhead channel. This overhead facilitates system synchronization and maintenance. Transmission performance and alarm conditions can be collected and forwarded to an operations system (OS). Many of the functions shown in Fig. 1 may be integrated into one system, in which the ADSL office units become "line cards" in an advanced switch or remote terminal.

The Concept of a Digital Subscriber Line Access Multiplexer — Recognizing ADSL and other DSL systems as a special class of data communication equipment, the concept of a digital subscriber line access multiplexer (DSLAM) has been proposed [9]. A DSLAM is configured as typical CO or RT telephone equipment with the traditional rack and panel structure and stringent operational environment requirement for a capability of 500 ADSL lines. A DSLAM can accept different flavors of DSL line cards. A DSLAM is designed to be connected to an ATM switch or an ATM cross-connect via the 155 Mb/s OC-3 interface. Initially, a DSLAM only needs to support permanent virtual connection (PVC). Switched virtual connection (SVC) will be required to support IP transport and other services. The conversion from PVC-based to SVC-based services can be provided through a software upgrade.

Data over ADSL will be encapsulated into ATM cells. A DSLAM needs to recognize ATM cells to perform statistical traffic multiplexing. The sum of ADSL line rates over all ATU-Cs can exceed the OC-3 line rate of the DSLAM network interface. To meet the quality of service (QoS) for ATM connections, some traffic buffering and queuing are necessary. Figure 2 depicts the general concept of a DSLAM.

For TCP/IP-based data traffic, the dedicated digital interface might not be efficient and necessary. Therefore, all ADSL channels can be first statistically multiplexed through a local area network (LAN) at the CO before being connected to the backbone data network. A LAN interface is required for each ADSL transceiver. The traffic external to the LAN is connected to a public or private computer network through a router. The concentrated data traffic might or might not be connected to the computer network through a digital switch. Because all ATU-Cs are close to each other and the LAN is only served as a traffic concentrator, the function of LAN and router can be combined to form a special purpose ADSL ATU-C concentrator. This concentrator could evolve to the DSLAM architecture if the ATM protocol is implemented over the concentrator and over ADSL links.

The Customer Premises Interface

Application of a POTS Splitter — A POTS splitter can be installed next to a network interface device (NID) as shown Fig. 3. Telephony devices are reconnected to the POTS splitter through existing in-house wiring. A new higher-quality wiring can also be installed to connect the POTS splitter to the ATU-R. In Fig. 3, the NID is at the entrance point of the telephone subscriber loop. The installation of a POTS splitter at this location allows the ATU-R to be placed near or inside a PC while avoiding the direct transmission of an ADSL signal over low quality telephone in-house wiring. Low quality in-house wiring with attached telephony devices can easily damage the performance of an ADSL system.

A POTS splitter could be included in an ATU-R. The ATU-R unit interfaces to the single loop pair on one side and demultiplexes POTS and ADSL channels on the other side. The ATU-R with the built-in POTS splitter can be placed near the NID. The POTS channel is routed to customer telephony devices via the existing in-house wiring. The ADSL channel can be connected to a PC or multiple PCs through the T interface as defined by the early ADSL standard.

The definition of the ADSL T interface is not an easy task. While low complexity is required for acceptance in the consumer market, the ADSL T interface needs a combined transmission throughput of more than 7 Mb/s with bidirectional multiple access points. For computer applications, the function of the T interface can be satisfied with a LAN such as 10BaseT or 100BaseTX. To carry video or telephony isochronous[2] traffic, the concept of a high throughput digital home network can be adapted to meet the demand of the ADSL T interface. This high throughput home network can be implemented with star topology data-grade twisted-pair cable based on the transmission protocol of IEEE P1394 [10]. The home network can also be shared with other networks or local information resources, as shown in Fig. 4.

Splitterless Possibilities — The idea of a splitterless ADSL has been recently proposed to simplify the initial deployment effort of the service. The simplicity of a voiceband modem is that a telephone company does not need to be involved if a PC is to be connected through the public switched telephone network (PSTN). In contrast, a technician visit is usually required to install an ISDN line. The installation involves not only the verification of an ISDN signal at the customer premises but sometimes also the installation of an ISDN router, and/or additional wiring. The installation of ADSL will be similar to that of ISDN if a splitter and/or additional wiring are required.

Without using a POTS splitter, the voiceband signal will be exposed to the ADSL transceiver and the ADSL signal will be exposed to telephone equipment such as a telephone set, an answering machine, or a fax machine. The effect of the POTS signal can be avoided by using a highpass filter inside an ADSL transceiver. On the other hand, the ADSL signal can cause a strong audible noise through a telephone set. The exposure of the upstream ADSL signal can also generate harmonics through nonlinear devices inside some telephone equipment to make the downstream channel unusable.

Recent ADSL field trials and standard group studies have shown that without using a POTS splitter a big percentage of customers will either experience very limited transmission throughput or audible POTS interference. For these cases, the distributed POTS splitter approach can be adapted. For this approach, the highpass filter portion of the POTS splitter is implemented inside an ADSL transceiver; the lowpass filter

[2] *Isochronous denotes continuous and delay-sensitive data traffic.*

portion is implemented as microfilters installed in conjunction with each telephony device. The microfilter, appearing as a telephone cable adapter, is connected between a telephony device and the in-house wiring. The installation of microfilters, which can be completed most of the time by ADSL users, prevents telephony devices from being exposed to ADSL signals.

It has also been confirmed in field trials that the effect of in-house wiring on the performance of ADSL is statistically minimal. A simulation study of the effect of the in-house wiring is provided in the appendix.

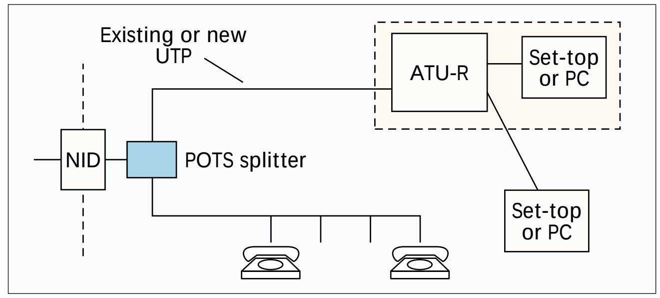

Figure 3. *An ATU-R with a separate POTS splitter.*

RECENT STANDARDIZATION EFFORTS ON ADSL

There are at least four major standards organizations and industry consortia engaged in ADSL-related activities. Progress is made through participants' technical contributions and discussions. Consensus is usually reached through compromises and condensed into official reference documents. Standards activity meetings are usually held monthly or quarterly. Participating companies usually have employees designated to attend these meetings. As a consequence of having multiple standards bodies involved in the same ADSL-related activities, many attendees are running around the globe to attend all these meetings. The positive effect of this redundant attendance is that these standards bodies are well synchronized.

T1E1.4 is the United States standards body involved with the development of DSL technologies as described in the beginning of this article. More information can be found at its Web site at http://www.t1.org/t1e1/_e14home.htm. Recent meetings were held August 31–September 3, 1998 in San Antonio, Texas, and November 30–December 3, 1998 in Plano, Texas. The draft ADSL standard document T1.413 issue 2 was recently made available for review. Compared with issue 1, topics such as STM and ATM transmission convergence layers, reduced overhead mode, the transmit PSDs, and loop timing are addressed. In addition, annexes on the definition of ADSL-NEXT, POTS low-pass filter, the ATM cell TC sublayer, and online (dynamic) rate adaptation are added. Although published as voluntary standards, previous technical documents about DSLs from T1E1.4 have been extensively referenced by the regional bell operating companies.

The ADSL Forum was formed in late 1994 to help telephone companies and their suppliers realize the enormous market potential of ADSL. More information can be found at its Web site at http://www.adsl.com/adsl_forum.html. Recent meetings were held September 15–18, 1998, in Singapore, and November 17–20, 1998 in Los Angeles, California. The ADSL Forum is dedicated to assist the telecommunications industry through its technical and marketing efforts. The Forum's marketing programs attempt to uncomplicate ADSL's inherent technical complexity and spread the news. Guidelines are given by the Forum's public technical report (TR) documents addressing technical issues complementing those from other standards bodies. TR001, released in May 1996, presents ADSL network and system reference models. TR002, released in March 1997, includes ATM over ADSL recommendations. TR003, released in June 1997, proposes framing and encapsulation standards for packet mode. TR004, released in December 1997, discusses network migration. TR005 through TR011, all released in March 1998, address, respectively: network element management; SNMP-based ADSL LINE MIB; customer premises; FUNI mode transport; channelization; packet mode; access networks; and an end-to-end packet mode architecture.

ITU has been very successful at defining standards for voiceband modems of varying speeds. More information can be found at its Web site at http://www.itu.int/itudoc/itu-t.html. As the top speed of a voiceband modem approaches the limit of channel capacity, many voiceband modem vendors turned their attention to ADSL in searching for the next more advanced product. Study group Q4/15 was formed in mid 1997 to speed up the development of xDSL and to encourage international acceptance. Recent ITU-T Q4/15 Rapporteur group meetings were held June 29–July 3, 1998 in Waikiki, Hawaii, and August 3–6, 1998 in Belgium. A recent ITU-T SG15 meeting was held October 12–23, 1998 in Geneva, Switzerland. A lower complexity and lower transmission throughput version of ADSL has been proposed as the G.lite standard. A working document that contains the issue list and a draft text for Recommendation G.lite has been developed. Issues the ITU group identified for G.lite include: idle mode and power management; fast retrain; Japanese time compressed multiplex (TCM) ISDN crosstalk environment; and interoperability between different equipment vendors. In addition, a handshake procedure to identify different flavors of DSL has been studied under Recommendation G.hs. Most recently, G.lite and G.hs have been officially named G.992.2 and G.994.1.

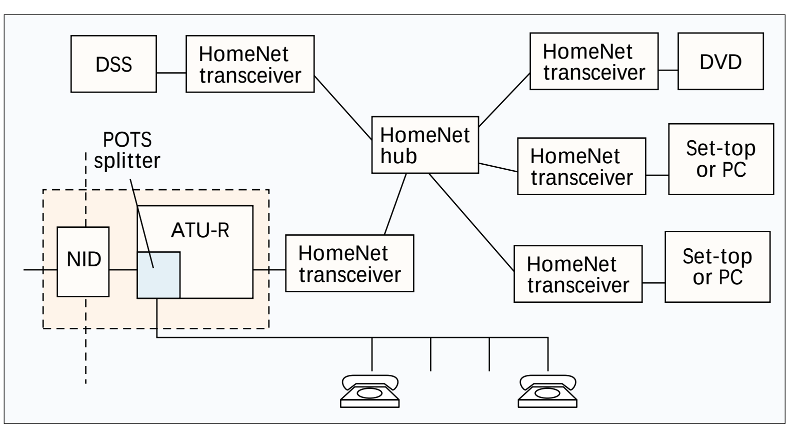

Figure 4. *ADSL connected to a home network.*

The Universal ADSL Working Group (UAWG) was formed at the beginning of 1998, promoted by COMPAQ, Intel, and Microsoft as another effort to shift to a high gear for the mass deployment of the ADSL technology. More information can be found at its Web site at http://www.uawg.org/. Promoters of this industry forum also include 13 major British, French, German, Japanese, Singapore and United States telephone companies. There are also 116 telecommunication companies listed as supporters, as well as many other adapters. Recent meetings were held September 29–30, 1998 in Chicago, Illinois, and October 29–30, in San Francisco, California. A draft framework document and a draft loop, impairment, and testing document have been prepared. In the framework document, procedures on dealing with idle mode and fast retrain have been addressed. In the second document, a variety of test loop and in-house wiring models have been proposed for the United States, Europe, and Japan. A number of crosstalk models are also defined for corresponding tests. Members of the UAWG group also participated in an extensive in-house wiring impedance and noise level measurement trial to gain direct experience about the in-house transmission environment.

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BIOGRAPHY

WALTER Y. CHEN (wchen@dma.isg.mot.com) has been involved with the development of digital subscriber line technology since 1989. As a research scientist at Bellcore, he was involved with the simulation study and development of HDSL and ADSL technologies for related standards. Between 1995 and 1997, he was involved with the development of a DSP-based version of ADSL transceiver at Texas Instruments. Currently, he is working with engineers at Motorola on the development of ADSL and home networking products. Dr. Chen is a summa cum laude graduate of the Polytechnic Institute of New York. He received an M.S. degree in electrical engineering from the California Institute of Technology and a Ph.D. in electrical engineering from the Polytechnic University of New York.

APPENDIX: THE EFFECT OF IN-HOUSE WIRING

Preliminary tests have shown some success in establishing an ADSL transmission link without the use of a splitter. The general topology of in-house wiring can be described as a star/daisy-chain configuration where a few branches of wiring cables are connected between the NID and phone jacks at different locations. A wiring branch can have a multiple number of phone jacks either bridged across the cable or attached to the branch with another cable. From the NID to a phone jack, the cable usually does not take the shortest length. Instead, the wiring cable can go through corners and/or the ceiling of a house. The wiring length can be further extended due to the practice of making cable connections at phone jack locations.

The transmission characteristics of in-house wiring can be studied in terms of wiring loss, branch loss, and reflection loss. It is found that wiring loss is insignificant compared with loss caused by branching and reflection. While the branch loss is related to the number of branches, the reflection loss is related to the cable length of the branch. A two-story house of average size has a dimension of 20 ft (height) x 30 ft (width) x 40 ft (length). The summation of all house dimensions is therefore 90 ft. Figure 5 shows the topology of a random in-house wiring model with section lengths labeled. It can be considered to have three wiring branches connecting the NID to three different areas of a house. In the first area there are three phone jacks, including phone jack A. In the second area there are two phone jacks, including phone jack B. In the third area, there are also two phone jacks, including phone jack C.

Figure 6 shows insertion loss from the NID to phone jack A compared with the loss when excluding the other two branches. All other phone jacks except the destination phone jack are not terminated. We can observe that the energy loss is primarily caused by branching. Furthermore, short branches, less than 20 ft, could not cause a frequency notch below 1.5 MHz. This random in-house wiring model introduced an insertion loss of less than 2 dB at a frequency band of up to 500 kHz.

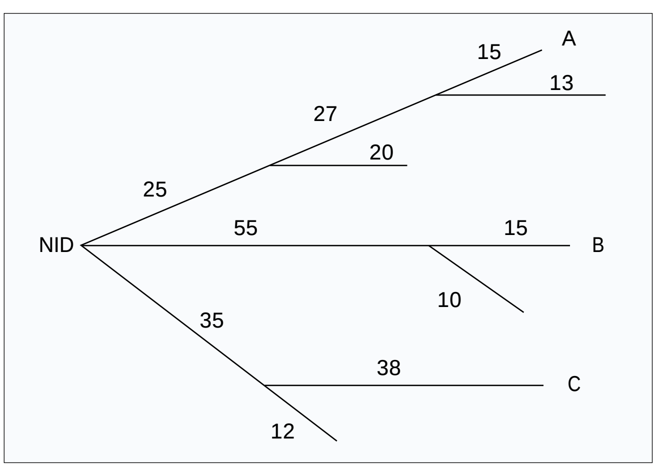

Figure 5. *A random in-house wiring model.*

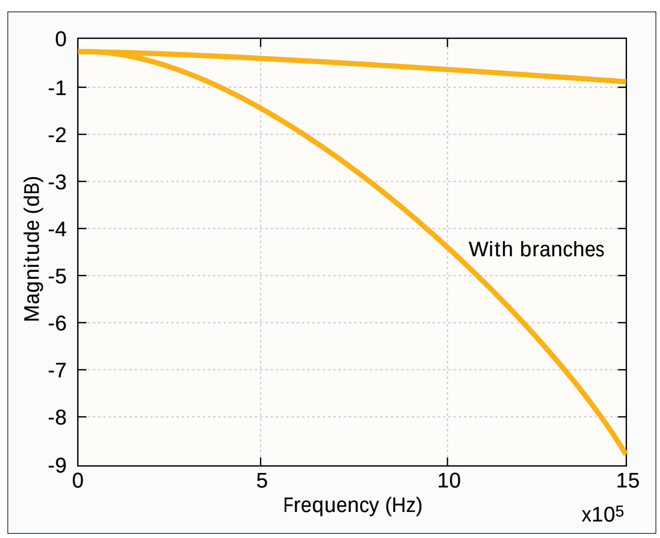

Figure 6. *The insertion loss from NID to point A.*