Asymmetrical digital subscriber line (ADSL) an in-depth study

John Kernan

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Asymmetrical Digital Subscriber Line (ADSL)

An In-Depth Study

By

John Kernan

Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Information Technology

Rochester Institute of Technology

B. Thomas Golisano College of Computing and Information Sciences

January 25, 2002
Rochester Institute of Technology
Department of Information Technology

Master of Science in Information Technology
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An In-Depth Study

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Master of Science in Information Technology

Asymmetrical Digital Subscriber Line (ADSL)

An In-Depth Study

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Abstract

Asymmetrical Digital Subscriber Line (ADSL) is one member of a group of broadband access technologies that uses the existing copper-based local loop of the analog PSTN for high-speed digital data transmission. One feature of ADSL is that it permits analog voice POTS transmissions to continue uninterrupted over the same wiring. Specifically, POTS continues to use the 0 to 4 KHz frequency range of the copper wiring, while ADSL uses bandwidth starting at 25 KHz and extending up to approximately 1.1 MHz for data transmission. The term “asymmetrical” refers to the fact that data rates downstream (to the user) and upstream (from the user) are not the same. Typical ADSL data rates range from 1.536 to 6.144 Mbps downstream and from 16 to 640 Kbps upstream. Local loop length, wire size, and the presence of devices to improve voice communication such as bridged taps and loading coils all affect ADSL data rates. Digital data is coded by one of two methods: Discrete Multitone Modulation (DMT) or Carrierless Amplitude and Phase Modulation (CAP). Echo control is also accomplished by one of two methods: Frequency Division Multiplexing (FDM) or echo cancellation.

This paper consists of four sections:

1) A technical review and comparison of the CAP and DMT line encoding technologies.

2) A market review of the presence of CAP and DMT technologies in customer premise equipment (CPE) such as modems and routers.

3) A review of the POTS physical layer that exists between the ADSL subscriber and the Telco CO, and its impact on ADSL availability and quality of service (QOS).

4) A technical review of the newer, splitterless, G.Lite technology
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I. The Technologies of ADSL

This section will discuss four aspects of the ADSL technology:

A) A review of analog and digital content and signals, line codes, and echo control.

B) The implementation of Discrete Multitone Modulation (DMT) for ADSL.

C) The implementation of Carrierless Amplitude and Phase Modulation (CAP) for ADSL.

D) A technical comparison between the CAP and DMT modulation technologies.

I-A) Technical Overviews

Analog & Digital Overview

There are two aspects to telecommunications:

1. *What* is being transmitted (the information content).

2. *How* the information is being carried (the signal). (This context of signaling should not be confused with that which the PSTN applies, which pertains to call control (how switched circuits carrying voice conversations are set up, maintained, and released)).

The information content may be either analog or digital; similarly, the signal carrying it may also be either analog or digital. Also, an interface device is required in order for a carrier signal to carry information content. This is summarized in Table 1:
Table 1 – Interface Devices

<table>
<thead>
<tr>
<th>Information</th>
<th>Signaling Method:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Content:</strong></td>
<td><strong>Analog</strong></td>
</tr>
<tr>
<td><strong>Analog</strong></td>
<td>Transducer</td>
</tr>
<tr>
<td><strong>Digital</strong></td>
<td>MODEM</td>
</tr>
</tbody>
</table>

For ADSL, the interface device used is a modem. More specifically, the interface device at the customer’s premises is referred to as an ADSL Transceiver Unit–Remote (ATU-R), and at the TELCO central office side (CO) as an ADSL Transceiver Unit–Central (ATU-C). The ATU-R at the customer’s side is either an external device or a card plugged into a PC. The ATU-C at the CO is a line card plugged into a DSL Access Multiplexer (DSLAM). POTS is maintained by the use of splitters at both the customer and CO locations, which separates the 0 – 4 KHz analog voice data from the higher frequency (25 KHz – 1.1 MHz) digital data of ADSL. The external ATU-R also often contains the splitter in it.

**Line Code Overview**

Line coding (how bits are sent) is the modulation method at the OSI physical layer used by ADSL. The ANSI standard line code (Standard T1.413) is Discrete Multitone Modulation (DMT). A competing, non-standard line code is Carrierless Amplitude and Phase Modulation (CAP), which is a variation of the Quadrature Amplitude Modulation (QAM) method. CAP (and QAM) are classified as single carrier modulation methods, where data modulates a single carrier that is transmitted across telephone lines. In
contrast, DMT is a multi-carrier modulation method, where data is collected and distributed over a maximum of 250 subchannels, with each subchannel using QAM.

**Echo Control Overview**

ADSL is a bi-directional full-duplex technology, which means that it can simultaneously send and receive digital data. In addition, the same frequency range over the same physical path is used during a full-duplex transmission. One drawback of full-duplex transmissions is the creation of echo, however. (Note that the context of “echo” here is not a reflected signal, but rather mutual signal interference resulting from simultaneous transmissions in opposing directions within the same frequency range over the same physical medium.) Regardless of the line coding method used (i.e., CAP or DMT), when the same wire pair is used for full-duplex operation, some form of echo control is needed.

The two methods used by ADSL are either Frequency Division Multiplexing (FDM) or echo cancellation (which will be referred to with the abbreviation “EC” from here on). The FDM method separates the upstream and downstream signals into different frequency ranges. In contrast, EC allows the upstream signal frequency range to overlap the downstream signal’s frequency range (remember, ADSL is asymmetric, meaning that there is more bandwidth for data transmission downstream than upstream, and therefore a larger frequency range allocated for downstream transmission). The physical separation of the upstream and downstream channels with FDM accomplishes echo control. With EC, both the upstream and downstream transceivers “remember” their transmitted signal. When a signal is subsequently received by each transceiver, if the “remembered” signal is
detected, it is extracted out leaving only the data of the intended signal present. Because of having separate frequency ranges for upstream and downstream transmissions and the need for a guardband separating the two, the disadvantage of FDM is reduced available bandwidth and therefore speed. The corresponding disadvantage of EC is increased modem cost due to the added circuitry needed to perform echo cancellation. Typically, CAP-modulated ADSL hardware uses FDM, whereas DMT-modulated ADSL hardware uses EC. If the ATU-R supports FDM, it is referred to as a “Category 1” modem, and if it supports EC it is a “Category 2” modem.

**Carrierless Amplitude and Phase (CAP) Modulation Overview**

CAP modulation is a variant of Quadrature Amplitude Modulation (QAM), a mature single-carrier modulation technique on which many voice-band modem specifications are based, such as V.32 and V.34. Therefore, in order to adequately discuss CAP, a discussion of QAM is required first.

**QAM Modulation**

QAM modulation uses the combination of a sine wave and a cosine wave at the same carrier frequency to transmit data. A property known as orthogonality, that exists between a sine and cosine wave, allows both waves to simultaneously transmit data over the same channel [Rauschmayer]. Since sine and cosine functions are 90 degrees out-of-phase, they are referred to as being in quadrature, and hence the origin of the term “quadrature”. Both waves are transmitted simultaneously over the same channel, with the amplitude of each wave conveying the encoding of a specific number of bits. The in-
phase cosine wave is referred to as the ‘I’ wave, while the 90-degree out-of-phase sine wave is referred to as the ‘Q’ (or quadrature) wave. The use of the sine ‘Q’ wave, combined with the process of amplitude modulation, results in the name quadrature amplitude modulation.

A simple binary modulated signal can exhibit only two possible states, and it can therefore transmit only a high or a low, or a ‘1’ or a ‘0’. In binary modulation the amplitude changes from a positive value to zero, and the data rate equals the baud rate. However, by using QAM more bits per baud can be transmitted. By combining amplitude and phase modulation of a carrier signal, the number of states increase, and therefore more bits can be transmitted per state change. It should be noted, however, that the number of states increases exponentially as the number of bits transmitted increase.

QAM-16 is commonly used as an example when discussing QAM. In QAM-16, the amplitudes of both the sine and cosine waves are modulated in order to obtain four different amplitudes for each wave. This permits two bits of information (which are coded as four different binary states: 00, 01, 10, 11) per wave, and four bits per wave pair, or symbol. This is also referred to as 4 bits per line condition, or “4 bits per baud” signaling. Again, however, four bits require a total of 16 binary states, thus resulting in the term “QAM-16”.

A more complex example of QAM is referred to as QAM-256, in which a total of 256 bit values are transmitted per QAM symbol, or one complete period (or baud) of each wave. In QAM-256, 4 bits are modulated per carrier wave, which results in 8 encoded bits per QAM symbol. With the ‘I’ and ‘Q’ wave amplitude-modulated independently of each
other with 16 levels of amplitude modulation, a total of 256 different amplitude levels from the combination of both waves is the result, which, in turn, yield 256 bit values per baud. The value of each encoded 8-bit combination is then mapped to 1 of 256 points contained on a QAM constellation, which is a two-dimensional graphing of each point (recall that 8 bits, or 1 byte, can have 256 different values). The x and y components of the point to which each 8-bit value is mapped correspond to the amplitudes of the cosine ‘I’ wave and sine ‘Q’ wave, respectively. To ensure that encoding and decoding is performed accurately, both the transmitter and receiver know the predetermined method of mapping each 8-bit value to a constellation point.

After the cosine ‘I’ and sine ‘Q’ waves are transmitted, at the receiver the amplitude of each wave is determined. The magnitudes of these estimated amplitudes are then projected onto a constellation identical to the one used by the transmitter. However, channel noise and distortion and electronic component tolerances in both the transmitter and receiver prevent the point projected by the receiver from coinciding exactly with the theoretical “true” point. To compensate, the receiver chooses the closest “true” constellation point to the projected point as the point the transmitter most likely used when generating the particular QAM symbol. This point is then mapped into the same number of bits that were used by the transmitter, but in the opposite direction.

Mapping errors can result if excessive noise at the receiver cause the projected point on the constellation to be located closer to a point other than the point the transmitter used for the particular QAM symbol. In the QAM-256 example, 8 bits would be mapped to each of 256 constellation points by both the transmitter and receiver. As a general rule, as the number of bits encoded per QAM symbol increases, the noise level required to cause
a constellation mapping error decreases. Said differently, QAM-256 requires a greater signal-to-noise ratio (SNR) than QAM-128 or less. It must be noted, however, that QAM tests the line condition prior to transmission, in order to optimize the QAM modulation level to be used. (Refer to Appendix B.)

CAP Modulation

CAP is closely related to QAM, and can best be described simply as “carrier suppressed QAM”. Since a carrier wave contains no data, its transmission can be dispensed with, so long as it is reconstructed at the receiver. Therefore, CAP can be roughly categorized as “carrierless” or “carrier suppressed” QAM line encoding. Also in common with QAM, CAP is a single-carrier modulation technique, which uses the entire bandwidth of the POTS local loop (except for the 0 – 4 KHz voice channel), with no subcarriers or subchannels. (In actuality, both QAM and CAP modulate a pair of waves, the ‘I’ and ‘Q’ waves, without subdividing either of them into subchannels.) In common with QAM, prior to transmission CAP tests line condition quality in order to optimize the level of modulation used in order to achieve satisfactory performance for a given line condition. CAP is a mature and well-understood technique, with many commercial and military applications proving its merit.

As discussed previously, QAM utilizes constellations whose points are a mapping of all possible bit value combinations resulting from the number of bits per symbol of the ‘I’ and ‘Q’ waves combined. Since CAP suppresses the carrier wave, the constellations are not “fixed” at an absolute value; rather, they are free to “rotate” about. In other words,
QAM and CAP waveforms will be identical if one of the sets of constellations used for encoding and decoding is rotated about the origin of the plane [Rauschmayer]. Herein lies the basic difference between the two: CAP and QAM differ in each one’s state representation of the constellation pattern. QAM performs data modulation in the analog domain, whereas CAP performs modulation digitally.

During the QAM modulation process, the encoded x and y values are sent to cosine and sine wave generators, respectively, with their orthogonal output being combined in the analog domain. CAP, however, uses the x and y values to excite digital filters, resulting in orthogonal signal modulation being executed digitally. The impulse responses of the digital filters are referred to as either Hilbert transform pairs or simply Hilbert pairs. So during modulation, the x and y components of a QAM modulated signal are subjected to in-phase and quadrature multipliers. In contrast, the x and y components of a CAP modulated signal are instead sent to two digital transversal bandpass filters with identical amplitude characteristics and having impulse responses that are orthogonal to one another (i.e., are Hilbert pairs). The following are equations for the x and y coordinates of a CAP-modulated constellation point:

\[ x \text{ coordinate: } h(t) = p(t)\cos(\omega t) \]
\[ y \text{ coordinate: } h'(t) = p(t)\sin(\omega t) \]

In the above equations: 1) \( h(t) \) and \( h'(t) \) represent the digital filters for the CAP-modulated x and y components, respectively; 2) \( p(t) \) is the shaping filter response (whose purpose is to reduce the bandwidth of the transmitted signal by filtering out higher-frequency components); and 3) \( \omega \) is a constant representing \( \pi/\text{period} \) \( \tau \).
In summary, CAP is basically QAM with the exceptions: 1) the carrier is suppressed at the transmitter and a rotation function present at the receiver, and 2) digital filters are used in place of sine and cosine wave generators during modulation.

Discrete Multitone (DMT) Modulation Overview

DMT is the official standard modulation method for ADSL, per the ANSI T1.413 standard of 1995. DMT divides the bandwidth of the copper-based POTS local loop into a maximum of 256 subchannels, subcarriers, or subbands, each occupying 4.3125 KHz, and yielding a resulting total bandwidth use of 1.104 MHz on the primarily copper-based the local loop. It is therefore referred to as a multi-carrier modulation technique, and with CAP being a single-carrier method, this results in being the most significant and basic difference between the two methods. Each one of DMT’s 4.3125 KHz-wide subbands is encoded at the transmitter by using a single-carrier modulation technique, commonly QAM, and the individual bit streams are then combined together at the receiver.

One very important feature of DMT, referred to as scalability, allows each subband to vary its spectral efficiency, which is a measure of the data transmission rate for a set amount of bandwidth. Since ADSL is transmitted over wired media, the noise present on each DMT subband can vary. Further, subbands containing high noise levels can be avoided altogether, existing as unused or “non-modulated” subbands in the total DMT frequency bandwidth. So, for example, subbands relatively noise-free can be QAM-64 encoded or greater, while subbands possessing lower spectral efficiencies can be encoded
by QAM-32 or QAM-16 methods. It is this property of scalability that makes DMT-modulated ADSL inherently rate adaptive to the end user.

DMT’s 256 subbands are allocated as follows for ADSL:

If using echo cancellation for echo control:

#1: POTS
#2 – 6: POTS Guardband
#7 – 38: Upstream Transmission
#7 – 256: Downstream Transmission (subbands #7 – 38 are echo cancelled to permit full-duplex transmission).

If using Frequency Division Multiplexing (FDM) for echo control:

#1: POTS
#2 – 6: POTS Guardband
#7 – 38: Upstream Transmission
#39 – 256: Downstream Transmission

Regardless of the method of echo control used, subbands #250 – 256 suffer from extreme signal attenuation and typically remain unused. Also, each subband beginning with #7 individually uses QAM for its line coding. Each subband’s gain (1 ÷ attenuation) is first determined, and then the optimum QAM modulation level for that subband’s gain level is used.
DMT is also known as *orthogonal frequency division multiplexing* (OFDM). A constellation encoder for each subband encodes a set of bits onto a point on a constellation, and the output value of the encoder is the amplitude of a sine and cosine wave. Since, however, DMT can utilize up to a maximum of 250 subbands, there can be up to 250 encoders, each providing a sine and cosine wave output at a different frequency. All of the sine and cosine waves are summed together and then transmitted as a single waveform. At the receiver, each pair of sine and cosine waves is extracted and decoded (Up to now, the term *subband* has been used to describe DMT’s 256 frequency channels (or subchannels or subcarriers). Two additional terms also used to describe frequency channels are *frequency bins* (or simply *bins*) and *DMT tones* (or simply *tones*).

It is important that the sine and cosine waves in each DMT bin be isolated from waveform pairs contained in adjacent bins. This is necessary in order to prevent decoding errors due to waveform corruption from adjacent waveforms. This is accomplished in DMT by 2 means:

1. Having the frequency in each bin be an integer multiple of a common frequency, referred to as the *fundamental frequency*; and
2. Having the symbol period ‘\( \tau \)’ be the inverse of the fundamental frequency.

In order to prevent waveform interference from adjacent bins, the sine and cosine waves in any bin need to be *orthogonal* to their counterparts in adjacent bins. As a result, DMT makes use of the orthogonality property of sine and cosine waves twice:
1. Between the sine and cosine waves within each bin ("intra-bin"); and
2. Between the sine and cosine waves between bins ("inter-bin").

DMT-modulated ADSL provides for a very adaptive access line service with built-in optimization of data rates. Bins with a high SNR are used for higher bit rate transmissions than bins with a lower SNR by using higher QAM levels. This occurs after the gain of each bin is determined.

**I-B) DMT ADSL Modulation Implementation**

The implementation of DMT ADSL modulation is according to the specification contained in ANSI T1.413. DMT ADSL is structured around a single physical channel that carries from two to seven logical data or bearer channels, and additional overhead channels. Each bearer channel carries both data and overhead, and of the seven, four are simplex downstream channels and three are full-duplex channels. Any of the four duplex channels can have different data rates in either direction (including zero), thus making them asymmetrical also. A typical ADSL implementation utilizes one each simplex downstream and duplex channels, with the duplex channel operating as a simplex upstream channel. Bin allocation with this implementation would be as follows:

- The duplex upstream channel transmits 32 bins (#7 - #38), regardless of the echo control method used.
- If using EC, the simplex downstream channel can transmit a maximum of 250 bins (#7 - #256).
- If using FDM, the simplex downstream channel can transmit a maximum of 218 bins (#39 - #256).

<table>
<thead>
<tr>
<th>Channel</th>
<th>Type</th>
<th>Data Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS0①</td>
<td>Simplex Downstream</td>
<td>0 – 6.144 Mbps</td>
</tr>
<tr>
<td>AS1</td>
<td>Simplex Downstream</td>
<td>0 – 4.608 Mbps</td>
</tr>
<tr>
<td>AS2</td>
<td>Simplex Downstream</td>
<td>0 – 3.072 Mbps</td>
</tr>
<tr>
<td>AS3</td>
<td>Simplex Downstream</td>
<td>0 – 1.536 Mbps</td>
</tr>
<tr>
<td>LS0②③</td>
<td>Full Duplex</td>
<td>0 – 640 Kbps</td>
</tr>
<tr>
<td>LS1③</td>
<td>Full Duplex</td>
<td>0 – 640 Kbps</td>
</tr>
<tr>
<td>LS2③</td>
<td>Full Duplex</td>
<td>0 – 640 Kbps</td>
</tr>
</tbody>
</table>

① AS0 is most commonly used as the lone downstream ADSL channel.
② LS0 is most commonly used as the lone upstream ADSL channel.
③ Duplex data rates can be asymmetrical.

DMT ADSL also organizes the bearer channels into one of four transport classes, whose purpose is to specify the maximum data rate of the bearer channels in order to insure interoperability [Goralski]. Each transport class (TC) is based upon a multiple of 1.536 Mbps data rate and they apply to both upstream and downstream bearer channels.
Table 3 – DMT ADSL Transport Classes

<table>
<thead>
<tr>
<th>Transport Class</th>
<th>Downstream Simplex</th>
<th>Upstream Duplex</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max. Rate (Mbps)</td>
<td>Bearer Channels</td>
</tr>
<tr>
<td>1</td>
<td>6.144</td>
<td>AS0, AS1, AS2, AS3</td>
</tr>
<tr>
<td>2</td>
<td>4.608</td>
<td>AS0, AS1, AS2</td>
</tr>
<tr>
<td>3</td>
<td>3.072</td>
<td>AS0, AS1</td>
</tr>
<tr>
<td>4</td>
<td>1.536</td>
<td>AS0</td>
</tr>
</tbody>
</table>

1 Mandatory transport classes
2 Optional transport classes

ADSL transmissions also utilize two types of paths: an *interleaved path* and a *fast path*. The interleaved path uses interleaving/de-interleaving functions in the transmitter and receiver, respectively; whereas the fast path does not. The purpose of the fast path is to transmit data bits which are delay-sensitive but noise tolerant, such as real-time audio and video data. In contrast, the interleaved path is used to transmit non-delay sensitive data such as that which occurs during file transfers and the loading of Web pages in a browser. Bits sent via the fast path (*fast data*) are buffered only for as long as it takes to format the frame they are to be sent in. Interleaved data sent via the interleaving path is buffered for a longer period of time in order for all of the bits to be “interleaved”. This interleaving process makes the data less susceptible to containing errors caused by impulse noise, but adds a latency penalty.

DMT ADSL utilizes an architecture containing both a *superframe structure* and a *framing structure*. A superframe is 17 ms long and is comprised of 68 predominantly
data-carrying frames, numbered 0 – 67, and a synchronization frame that carries no user data. Each frame corresponds to a single ADSL symbol and has a duration of approximately 250 microseconds, resulting in a frequency of 4 KHz. Each frame also consists of two parts: a fast buffer and an interleaved buffer. Each data frame contained in a superframe allocates a specified number of bytes in both the fast and interleaved buffers for each bearer channel in use. Note, however, that the ANSI standard does not specify how or which used bit streams must occupy the fast and interleaved buffers in a frame.

Downstream data frames can contain data from all seven bearer channels (AS0 – AS3, LS0, LS1, LS2), while upstream data frames can accommodate data only from the duplex bearer channels LS0, LS1, LS2. The following illustrates the general makeup of a DMT ADSL data frame:

<table>
<thead>
<tr>
<th>Fast Buffer</th>
<th>Interleaved Buffer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Overhead</td>
<td>Fast Data</td>
</tr>
<tr>
<td>Fast Overhead</td>
<td>Interleaved Overhead</td>
</tr>
<tr>
<td>Interleaved Data</td>
<td>Interleaved Overhead</td>
</tr>
</tbody>
</table>

For either the fast or interleaved paths, the general makeup of the data carrying portion of the fast and interleaved buffers is as follows:

<table>
<thead>
<tr>
<th>AS0 Bytes</th>
<th>AS1 Bytes</th>
<th>AS2 Bytes</th>
<th>AS3 Bytes</th>
<th>LS0 Bytes</th>
<th>LS1 Bytes</th>
<th>LS2 Bytes</th>
</tr>
</thead>
</table>

**Downstream Transmission**

<table>
<thead>
<tr>
<th>LS0 Bytes</th>
<th>LS1 Bytes</th>
<th>LS2 Bytes</th>
</tr>
</thead>
</table>

**Upstream Transmission**
Since bytes or octets of data are allocated for each bearer channel in a data frame, and the rate of a DMT ADSL symbol is 4 KHz, the corresponding data rate of each bearer channel must be in multiples of 32 Kbps. This is referred to as the \textit{granularity} of a DMT – modulated ADSL service. The data rate of any DMT ADSL bearer channel can be computed by the following:

\[
R_{\text{channel}} = \frac{\# \text{ data bytes} \times 8 \text{ bits} \times 4000 \text{ data frames}}{\text{frame} \times \text{byte} \times \text{sec}}
\]

In additional to the primarily data carrying bearer channels, a DMT modulated ADSL transmission also includes a number of channels dedicated to carrying overhead information. This overhead consists of the embedded operations channel (EOC) and the ADSL overhead channel (AOC). The EOC is used by the ATU-C and ATU-R to communicate between each other. Examples of EOC overhead include self-test results, line attenuation, SNR, and general configuration information. The EOC protocol establishes the ATU-C as the master of the channel and the ATU-R as the slave, and uses a message/echo response scheme [Rauschmayer].

The AOC is used by the ATU-C and ATU-R for the specific purpose of \textit{bit swapping}. Bit swapping is the process where the size of the QAM constellation contained in each bin of a DMT modulated ADSL transmission can be dynamically changed. Based upon the SNR of each bin, the receiver makes requests to the transmitter to add or remove bits between bins, which results in increasing or decreasing the size of the QAM constellation in each bin and thus optimizing each bin’s SNR. A second purpose of the AOC is to adjust the power level of each bin. Again, this occurs as the result of a request being
made by the receiver to the transmitter. In response to both bit swapping and power adjustment requests made by the receiver, the transmitter sends back an acknowledgement.

In each superframe, a total of 24 indicator bits (ibs) are sent. In particular, one overhead byte in each of frame 1, frame 34, and frame 35 make up the 24 total indicator bits per superframe. The primary role of the ibs are to convey information between the ATU-C and ATU-R regarding the following in the previous superframe sent:

- If cyclic redundancy check (CRC) errors were present.
- If forward error correction (FEC) was required to correct any incorrectly decoded bits during demodulation at the ATU-R.
- If any signal loss occurred.
- If a remote default indication (rdi), where two consecutive synchronization frames have been incorrectly received at the ATU-R, is present.
- Various additional information if asynchronous transfer mode (ATM) cells are being transmitted by ADSL.

**Framing**

The fast buffer portion of a DMT ADSL data frame begins with overhead known as a fast path synchronization byte, or simply fast byte. The fast byte is always present, even if no fast paths are being utilized by any bearer channels. Depending upon the frame number, fast bytes have four functions:

1. Carrying the CRC value for the fast channel of the preceding superframe (frame 0).
2. Carrying *indicator bits* (frames 1, 34, & 35).

3. Carrying embedded operations channel (EOC) information.


The fast bytes in frames 2 – 33 and 36 – 67 are used to carry either EOC data or synchronization control information.

The counterpart to the fast byte in the interleaved portion of a data frame is the *sync byte*. The sync byte also performs four functions:

1. Carrying the CRC value for the interleaved channel of the preceding superframe (frame 0).

2. Carrying synchronization control information for byte stuffing/robbing.

3. When the interleaved path is being used, indicates that the LEX byte is carrying AOC information.

4. Carrying AOC information when the interleaved path is not being used by any bearer channels.

With the exception of the first function indicated, which is performed only by the sync byte in frame 0, the sync bytes in each of frames 1 – 67 carry bits dealing with the remaining three functions listed.

The AEX and LEX bytes are additional overhead contained in the seven bearer channels, and are used to add or delete bits from frames in the AS and LS bearer channels, regardless of either fast or interleaved paths being used. An AS channel can have up to 2 bytes added or *stuffed*, resulting in both an AEX and LEX byte, or one byte deleted or
robbed. An LS channel can have only one byte stuffed (LEX byte) or robbed. The purpose of byte stuffing/robbing is to equalize a bearer channel to the exact rate needed for transport, thus preventing buffer overflow or “underflow”.

DMT ADSL Data Frame Detail:

<table>
<thead>
<tr>
<th>Fast Byte</th>
<th>AS0 Bytes</th>
<th>AS1 Bytes</th>
<th>AS2 Bytes</th>
<th>AS3 Bytes</th>
<th>LS0 Bytes</th>
<th>LS1 Bytes</th>
<th>LS2 Bytes</th>
<th>AEX Byte</th>
<th>LEX Byte</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Fast Path Downstream</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sync Byte</th>
<th>AS0 Bytes</th>
<th>AS1 Bytes</th>
<th>AS2 Bytes</th>
<th>AS3 Bytes</th>
<th>LS0 Bytes</th>
<th>LS1 Bytes</th>
<th>LS2 Bytes</th>
<th>AEX Byte</th>
<th>LEX Byte</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Interleaved Path Downstream</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fast Byte</th>
<th>LS0 Bytes</th>
<th>LS1 Bytes</th>
<th>LS2 Bytes</th>
<th>LEX Byte</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. Fast Path Upstream</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sync Byte</th>
<th>LS0 Bytes</th>
<th>LS1 Bytes</th>
<th>LS2 Bytes</th>
<th>LEX Byte</th>
</tr>
</thead>
<tbody>
<tr>
<td>4. Interleaved Path Upstream</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The preceding frame examples represent the makeup of the four types of data frames that can be present in a DMT ADSL superframe following the “framing” operation, the input to which consists of the selected bearer channels, EOC and AOC information, the ibs, and the data itself.

As discussed above, an 8-bit CRC value is computed for both the fast and interleaved paths of each superframe and is sent in corresponding fast and sync bytes of the first frame (frame 0) of the following superframe. From a functional perspective, this is
performed after the framing function. The purpose of the CRC is to keep track of how many previous superframes were received with errors that could not be corrected by FEC.

**Scrambling**

ADSL employs a scrambler at the transmitter and a corresponding descrambler at the receiver. The purpose of scrambling is not for data encryption or security purposes, but to simply randomize data. Randomized data, lacking long strings of consecutive ones and zero’s, helps to insure that processes such as timing recovery phase lock loops and adaptive equalization algorithms function properly. Scrambling (and descrambling) is performed independently for both the fast and interleaved paths. All bits in all bearer channels are scrambled with the exception of those contained in the sync frame of every superframe.

**Forward Error Correction**

After scrambling, the next function performed is forward error correction (FEC). The purpose of FEC is to add a small amount of redundancy to the transmitted payload. The purpose of this redundant data is to permit the receiver to correct errors resulting from incorrect bit decoding during demodulation. Again, data contained in both the fast and interleaved paths have FEC applied independently of each other. A commonly used technique is Reed-Solomon (RS) coding [Rauschmayer], which is classified as a cyclic block code.
An RS encoded ADSL system uses codewords consisting of a constant number of both data bytes and check bytes. The size of a codeword is determined during initialization of the ADSL link, but is always less than 255 bytes [Rauschmayer]. A single codeword is sent for each fast path data frame. For the interleaved path the codeword can contain 1, 2, 4, 8, or 16 interleaved data frames. For both paths the number of check bytes can be any even number up to 16, inclusive. As a rule-of-thumb, the ratio of check bytes to data payload bytes should be in the range of 0.1 [Rauschmayer]. The advantage of using RS-based FEC is that it permits the receiver to detect and correct data transmission errors without the need for data retransmission. The number of byte errors that a Reed-Solomon decoder can correct at the receiver is half the total number of check bytes used.

With the addition of the scrambling, CRC and FEC functions, default buffer allocations for downstream DMT ADSL data frames of transport class 1 now appear as follows:

<table>
<thead>
<tr>
<th>Fast Byte</th>
<th>AS0 Bytes</th>
<th>AS1 Bytes</th>
<th>AS2 Bytes</th>
<th>AS3 Bytes</th>
<th>LS0 Bytes</th>
<th>LS1 Bytes (5)</th>
<th>LS2 Bytes (12)</th>
<th>AEX Byte</th>
<th>LEX Byte</th>
<th>Reed Solomon Check Bytes (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Path Downstream</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sync Byte</th>
<th>AS0 Bytes (96)</th>
<th>AS1 Bytes (96)</th>
<th>AS2 Bytes</th>
<th>AS3 Bytes</th>
<th>LS0 Bytes (2)</th>
<th>LS1 Bytes</th>
<th>LS2 Bytes</th>
<th>AEX Byte</th>
<th>LEX Byte</th>
<th>Reed Solomon Check Bytes (16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interleaved Path Downstream</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Also, with the addition of scrambling, CRC and FEC, *upstream* DMT ADSL data frames now appear as follows (note that ANSI T1.413 *does not* specify upstream default buffer allocations from the ATU-R to the ATU-C):

<table>
<thead>
<tr>
<th>Fast Byte</th>
<th>LS0 Bytes</th>
<th>LS1 Bytes</th>
<th>LS2 Bytes</th>
<th>LEX Byte</th>
<th>Reed Solomon Check Byte(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Path Upstream</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sync Byte</th>
<th>LS0 Bytes</th>
<th>LS1 Bytes</th>
<th>LS2 Bytes</th>
<th>LEX Byte</th>
<th>Reed Solomon Check Byte(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interleaved Path Upstream</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Interleaving**

Interleaving has been previously discussed numerous times as being the alternative path to the fast path for ADSL data transmission. However, the actual application of the interleaving function occurs after the Reed-Solomon FEC encoding function in a DMT ADSL transmission. As stated previously, impulse noise encountered during transmission can cause bit errors, and often on consecutive numbers of bits. Although a Reed-Solomon decoder is capable of correcting a quantity of damaged bytes equal to half the total number of check bytes in use, a group of consecutively damaged bits due to impulse noise can often overwhelm this capability. If long strings of erred bits are grouped together, the Reed-Solomon technique is unable to identify them.

The interleaving function reorders the data bits within an RS codeword prior to transmission. Should a consecutive number of these reordered bits be damaged during transmission (typically due to impulse noise), the effect at the receiver will be minimal to
non-existent. The de-interleaver at the receiver reorders the bits back into their original order as assembled in the original RS codeword at the transmitter. Thus, any series of consecutively damaged bits received within an RS codeword are now randomly dispersed within the RS codeword and are well within the capability of FEC decoding. The process that DMT ADSL uses is known as convolutional interleaving/de-interleaving. To summarize, if a long string of damaged bits were originally present within a received RS codeword, the damaged bits become intermittently dispersed within the RS codeword after de-interleaving, which greatly reduces the chance of FEC becoming overwhelmed and unable to correct the errors.

As stated previously in the discussion of the fast and interleaved data paths, the penalty for bit interleaving is transmission latency. Time is required to extract bits from the data stream and redistribute them in an interleave buffer, apply FEC, and then reinsert them into the data stream. As would be expected, latency increases with the amount of bit interleaving being performed. In addition, buffers are required at both the transmitter and receiver for interleaving and de-interleaving.

**DMT Modulator - Tone Ordering and Constellation Encoding**

Prior to actual modulation, the data to be transmitted resides in both a fast channel data buffer and an interleaved channel data buffer. To be modulated, the required number of bits allocated for each DMT bin must be extracted from both data buffers and:

1. Assigned to an audio tone (*tone ordering*).
2. Encoded into a complex number \( Z_i \) (constellation encoding), where \( 'i' \) refers to a particular bin or subchannel.

Tone ordering is a process that assigns a unique audio tone to each bin. It requires that the number of bits assigned to each bin are known in advance. This is determined during \textit{startup training}, when all bins are analyzed. The result of startup training is that both the transmitter and receiver will know how many bits will be carried by each bin \((bi\ value)\) during transmission. Each bin’s bi value must be between 2 and 15; otherwise, it must be zero. This process of assigning variable numbers of bits to each bin is known as \textit{bit loading} [Schlegel]. The sum of all bi values equals the number of bits contained in both the fast and interleaved portions of an ADSL data frame. Bits from the fast buffer are assigned to bins with low bi values, which therefore results in the bins with higher bi values carrying bits from the interleaved buffer. Because fast path bins have low bi values, any damaged bits in an ADSL symbol can usually be corrected by FEC at the receiver. Any damaged bits contained in the higher bi value interleaved path bins, though more numerous than those contained in fast path bins, will be corrected by a combination of interleaving and FEC.

After bits are allocated to each bin, QAM modulation takes place. Each bin is independently encoded, and the output of each bin’s constellation encoder \((Z_i)\) is a complex value. The real part represents the cosine \('I' wave’s \) amplitude and the imaginary part represents the sine \('Q' wave’s \) amplitude. The number of points in each bin’s QAM constellation depends upon each bin’s bi value. Since bi values can range
between 2 and 15, constellation sizes can range from having $4 \times 2^2$ to $32,768 \times 2^{15}$ points. For empty bins the outputs of the appropriate constellation encoders are zero. For DMT ADSL, a maximum of 250 bins exist in the downstream direction, resulting in up to 250 complex QAM encoder output values, and 32 bins upstream, resulting in 32 complex values.

The following will illustrate the transmission rates of an idealized DMT-modulated ADSL transmission, with each bin QAM-64 (6 bits/symbol) encoded, with 250 downstream bins and 32 upstream utilized:

**Downstream:**

$$250 \times (6 \text{ bits/symbol}) \times (4.3125 \times 10^3 \text{ cycles/sec.}) \times (1 \text{ symbol/cycle}) = 6.469 \text{ Mbps}$$

**Upstream:**

$$32 \times (6 \text{ bits/symbol}) \times (4.3125 \times 10^3 \text{ cycles/sec.}) \times (1 \text{ symbol/cycle}) = 828 \text{ Kbps}$$

**DMT Modulator - Frequency to Time Domain Conversion**

The downstream DMT ADSL transmission in comprised of 250 audio tones. Each tone corresponds to a bin, and they are spaced 4.3125 KHz apart. The center of the first tone is at 4.3125 KHz and the center of the 256th tone is at 1.104 MHz (recall that bin #1 is used for POTS and bins 2 – 6 serve as a POTS guardband). Each bin’s bi value is QAM-encoded, which results in a complex encoder output value being assigned to each bin. Each bin’s complex QAM “subsymbol” is next subjected to an inverse fast fourier transform (IFFT), which transforms each complex frequency-domain value into a pair of
real time-domain values. These resulting 512 real values are then processed by a parallel-to-serial converter and have frequency division multiplexing performed.

The upstream DMT ADSL signal is comprised of 32 tones, with the corresponding 32 complex QAM encoder output values resulting in 64 real time-domain values following the application of the IFFT at the modulator. Parallel-to-serial conversion and FDM are then performed. Tone spacing is again 4.3125 KHz, with the centers of the first and last (32\textsuperscript{nd}) tone being 4.3125 KHz and 138 KHz, respectively.

**Cyclic Prefix**

Communication systems that operate near their theoretical limits employ what is known as equalization in both the transmitter and receiver to optimize their transmission [Rauschmayer]. One way in which a DMT ADSL transmission can be equalized is by removing or preventing *inter-symbol interference* (ISI) between DMT symbols [Tomasetti]. The addition of a cyclic prefix to each DMT symbol after the parallel to serial conversion has been performed prevents ISI and also preserves orthogonality between bins [Bengtsson]. For a downstream transmission the last 32 of 512 values in a DMT symbol (480 – 511) are copied to the beginning of the symbol, resulting in the symbol now containing 544 real values. For an upstream transmission the last 4 values are added as a prefix to the DMT symbol, resulting in the upstream symbol now containing 68 real values. In either case, this has the result of making the transmitted symbol appear to be circular or periodic [Schlegel]. The effect of this is the creation of a
guard space between adjacent symbols in the time domain, which effectively combats ISI [Schlegel].

**Digital-to-Analog Conversion**

The last processes that occur prior to the transmission of a DMT-modulated ADSL signal are digital-to-analog conversion and low-pass filtering.
Echo Control

Echo control is also performed during modulation and demodulation. The ANSI DMT ADSL specification allows the transmitted signal a choice between either frequency division multiplexing (FDM) or echo cancellation (EC). However, based upon numerous sources researched [Aber, Goralski, Huttle, Lane, etc.], DMT-modulated ADSL systems typically are portrayed using EC (and CAP-modulated systems typically with FDM).

With FDM, a duplex transmission over the physical plant is accomplished by assigning different frequency bands for downstream and upstream ADSL transmissions. When using EC, the upstream band overlaps a portion of the larger downstream band. (Refer to Appendix A.)
When DMT-modulated ADSL employs EC, an exact replica of the transmitted signal that leaks into the receiver is recreated at the receiver. This “echo replica” is then subtracted from the received signal, effectively eliminating the echo. The disadvantage to this added signal processing, as can be expected, is increased complexity and cost of a “Category 2” ADSL modem. However, rapidly decreasing costs for the manufacture of VLSI DSPs (very large-scale integrated circuit digital signal processors) is minimizing this drawback.

One disadvantage of using EC, however, is the presence of near-end crosstalk (NEXT) at the ATU-R of a DMT-modulated ADSL signal. NEXT is where a user at one ATU-R location, while receiving a downstream transmission, also receives spurious upstream transmissions from one or more other ATU-R locations, hence the crosstalk originates only at the “near end” of the ADSL deployment. Said another way, NEXT is characterized by the disturbing (wire) pairs’s source being local to the disturbed (wire) pair’s receiver [Rauschmayer]. This is due to the fact that the downstream signal frequency range used by the ATU-C overlaps the entire 30 KHz to 138 KHz upstream signal frequency range used by local transmitters within the ATU-R. Thus, NEXT is present only in this shared frequency range, and is absent from all downstream frequencies above 138 KHz (and which only originate from the ATU-C). The actual cause of NEXT is interference that occurs among adjacent wires contained in a POTS “binder group” [Abe]. Since all of the wires are unshielded, interference occurs between wires due to the presence of electromagnetic coupling.
DMT ADSL Demodulation

At the receiver, demodulation of the DMT ADSL transmission takes place. It is basically the reverse of the modulation process at the transmitter, and therefore will only be reviewed in an outline format:

- Perform analog-to-digital conversion.
- Apply time-domain equalization.
- Removal of the cyclic prefix.
- Conversion of the 512 (or 64 for upstream) real time-domain values back to 256 (or 32 for upstream) complex frequency-domain values by using a fast fourier transform (FFT).
- Apply frequency-domain equalization.
- Decode the payload of each bin by using a QAM constellation decoder.
- Extract the bits from each bin and redistribute them in the fast and interleaved buffers.
- Perform de-interleaving of the interleaved path.
- Perform Reed-Solomon decoding.
- Perform de-scrambling.
- Submit the fast and interleaved bit streams to a CRC check.
- Perform de-framing and decode the fast and sync bytes.
I-C) CAP ADSL Modulation Implementation

The implementation of CAP ADSL modulation is according to the specification proposed in ANSI T1E1.4/97-104R2a. The framing structure proposed differs considerably from its DMT-modulated ANSI standard counterpart:

- There is a single physical channel which also serves as the lone logical channel.
- There is no use of either a superframe or a synchronization frame.
- A frame is a fixed 432 bytes in length.
- The time duration of a frame is variable, being a function of both the baud and bit rates of the CAP ADSL transmission.
- CAP ADSL has a typical granularity of 340 Kbps downstream and 54 Kbps upstream, with either being attained by varying both the constellation size and bandwidth of the single carrier [Baines].
Closely related to granularity, CAP ADSL utilizes a small number of set symbol rates:

*Downstream:* 340, 680, or 952 ksymbols/sec.

*Upstream:* 84 or 136 ksymbols/sec.

The framing block proposed for CAP modulated ADSL is shown below.

<table>
<thead>
<tr>
<th>Synchronization Word</th>
<th>FEBE</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 bits</td>
<td>1 bit</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>424 bytes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dying Gasp</th>
<th>Reserved</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 bit</td>
<td>7 bits</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EOC</th>
<th>Growth</th>
<th>NTR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 byte</td>
<td>3 bytes</td>
<td>1 byte</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CRC-6</th>
<th>RAI</th>
<th>Reserved</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 bits</td>
<td>1 bit</td>
<td>1 bit</td>
</tr>
</tbody>
</table>

**CAP ADSL Frame Field Breakdown:**

- **Synchronization Word** – 7-bit code used for delineating frames.

- **Far End Block Error (FEBE)** – Indicates that errors are present in a received frame.

- **Data** – 424 bytes capacity.

- **“Dying Gasp”** – Set = 1 by the ATU-R if a loss of power is detected.

- **Reserved** – 7 bits reserved for future use.

- **Embedded Operations Channel (EOC)** – transmission of EOC information.
• Growth – 3 bytes reserved for future use.

• Network Timing Reference (NTR) – 1 byte reserved for future network timing reference use.

• CRC-6 – 6-bit CRC checksum for the current frame.

• Remote Alarm Indication (RAI) – Indicates that the receiver is unable to delineate between frames.

Forward Error Correction

In common with DMT-modulated ADSL, Reed-Solomon coding and decoding is used for FEC of “bursty” errors, which can result from a variety of sources of interference during transmission. The default codeword size is 68 bytes, 4 of which being check bytes. If supported by the ATU-R, a variable-size codeword may be used [Rauschmayer]. The number of data bytes can vary, but 4 check bytes remain in use.

Interleaving

In common with the DMT-modulated variant, a convolutional interleaver is employed by CAP-modulated ADSL.

Scrambling

The only noteworthy difference between CAP-modulated ADSL versus its DMT-modulated counterpart is that scrambling occurs after FEC when CAP-modulated, not before, as when DMT-modulated. Otherwise, the incoming bit stream is randomized and input to the trellis encoder.
Trellis Encoding

In contrast to DMT-modulated ADSL, which adds a cyclic prefix value to each symbol to control inter-symbol interference (ISI), CAP ADSL uses trellis encoding in order to accomplish signal equalization. Trellis encoding is a form of convolutional encoding, a method of FEC applied to one or a few bits of serial data at a time [Fleming]. In CAP ADSL, the 2 LSBs of each symbol are input to the trellis encoder, and a single coded bit is output [Rauschmayer]. Thus, for N bits per symbol input, (N + 1) bits are output.

The basic principle behind trellis encoding is to cause a dependency between symbols, which are represented as points on a CAP constellation. More constellation points are used than necessary in order to represent all bit combinations to be encoded. This increases the linear (or Euclidean) distance between constellation points, which reduces the adverse affect of noise during transmission on each symbol. By doubling the number of constellation points (by increasing the exponent ‘N’ to “N + 1”), and partitioning, a number of new, smaller constellations are created, with each one being a subset of original ‘N’ constellation. This results in there being a greater distance between points in each “subconstellation” than if the points were contained in the original, single constellation. This, in turn, permits the receiver to more accurately decode which symbol point was sent, even in the presence of noise [Eicon].

It was noted above that trellis encoding doubles the number of points contained in a CAP symbol constellation. Take CAP-64, for example. Before the extra bit resulting from
trellis encoding is added, $N = 6$ bits/symbol, and the size of the constellation is 64 points (i.e., $2^6$). After trellis encoding, there are now 7 bits/symbol, and the constellation now contains 128 ($2^7$) points. While at first it may seem that doubling the number of constellation points while keeping the symbol rate the same would lower the SNR of the transmission, this is not the case. On the contrary, "as increasing the number of points and adding point redundancy considerably improves the quality and the reliability of the system" [Zsolt]. Finally, this hybrid error detection scheme of using the previously discussed Reed-Solomon FEC combined with trellis encoding is believed to offer improved error detection/correction performance for CAP-based ADSL [Rosner].

**CAP Modulator-Constellation Encoder**

The CAP encoder receives as input an interleaved and scrambled bit stream that now also contains a trellis encoding bit, and encodes the bit stream into a CAP symbol. Each CAP symbol is mapped to a point on a constellation diagram and is represented by a complex equation of the form:

$$A_n = a_n + jb_n$$

For each CAP symbol, the constellation diagram is constructed by mapping each symbol such that the real part of the complex number is plotted on the in-phase 'I' axis (x-axis) and the imaginary part on the quadrature ‘Q’ axis (y-axis) on a 2-dimensional map. The size of a CAP constellation can range from 8 ($2^3$) to 256 ($2^8$) points [Rauschmayer]. So, using CAP-256 as an example, there would be 256 constellation points, each of which represented by a unique complex equation, and with each equation representing the value of 8 bits of data.
The following will illustrate the transmission rates of an idealized CAP-modulated ADSL transmission, using CAP-256 (8 bits/symbol) encoding, and utilizing a frequency range of 240 KHz – 1.1 MHz downstream and 25 – 160 KHz upstream:

**Downstream:**

\[(8 \text{ bits/symbol}) \times (0.86E6 \text{ cycles/sec.}) \times (1 \text{ symbol/cycle}) = 6.88 \text{ Mbps}\]

**Upstream:**

\[(8 \text{ bits/symbol}) \times (1.35E3 \text{ cycles/sec.}) \times (1 \text{ symbol/cycle}) = 1.08 \text{ Mbps}\]

**CAP Modulator-Digital Filtering**

The next phase of CAP modulation is to obtain the \(a_n\) and \(b_n\) coefficient values (with ‘n’ designating the \(n^{th}\) symbol period) and use them as discrete impulses to excite a pair of digital filters [Rauschmayer]. The \(a_n\) path contains the real-value coefficients and the \(b_n\) path the coefficients of the imaginary values of the complex equations representing each constellation point. The symbol stream containing the coefficients of each real-value term is input to a passband in-phase shaping filter, while the symbol stream containing the imaginary coefficients is input to a quadrature shaping filter. The input responses (i.e., their output) of the digital filter pair is referred to as a *Hilbert transform pair* or simply a *Hilbert pair*. One property of a Hilbert pair is that the values are orthogonal to one another, therefore resulting in orthogonal signal modulation of the complex input [Baines]. Thus, each CAP ADSL symbol is represented by a Hilbert pair, one being an in-phase component and the other an orthogonal quadrature component. The Hilbert pair values are then summed into a single signal. (This again illustrates the main difference
between CAP and QAM signal modulation: CAP performs signal modulation digitally whereas QAM uses analog cosine and sine wave generators [Rauschmayer].

**Digital-to-Analog Conversion**

The last processes that occur prior to the transmission of a CAP-modulated ADSL signal are digital-to-analog conversion and low-pass filtering, which filters out the 4 KHz. POTS transmission.
As stated previously, echo cancellation (EC) appears to be the method of multiplexing commonly used in DMT-modulated ADSL. In contrast, CAP-modulated systems all seem to use frequency division multiplexing. Frequency-division multiplexing (FDM) permits the full-duplex operation of a CAP-modulated ADSL transmission, and, as a consequence, accomplishes echo control in the process. One advantage of FDM versus EC is its invulnerability to “near-end crosstalk” (NEXT). This is due to the fact that FDM uses non-overlapping frequency bands to obtain independent upstream and downstream transmissions, thus NEXT is avoided. In contrast, EC-multiplexed ADSL transmissions must recreate and “cancel-out” the echo at reception.
CAP ADSL Demodulation

The CAP ADSL demodulator operates on a symbol-by-symbol basis and decodes at the baud rate of the system [Rauschmayer]. Symbols are decoded using a constellation identical to that used during modulation. The following outlines the CAP ADSL demodulation process:

- Perform analog-to-digital conversion and send output to a matched pair of digital filters.
- Extract the in-phase and quadrature components for each constellation point by the respective filter.
- Map these in-phase and quadrature components as the coordinates of points on a constellation identical to that used during modulation, including the trellis output bit.
- Perform trellis decoding of each constellation, which converts the reconstructed trellis-encoded constellation for each CAP symbol into the original binary data input to the trellis encoder at the transmitter (i.e., minus the trellis coding bit). This is accomplished by applying a Viterbi decoding algorithm.
- Perform de-scrambling of the binary data stream.
- Perform de-interleaving of the binary data stream.
- Perform Reed-Solomon decoding.
- Perform de-framing.
I-D) DMT vs. CAP Technical Comparison

DMT is generally considered technically more complex than CAP but is the ADSL line code standard selected by ANSI (T1.413-1995). It has also been selected internationally as the ADSL line code standard over a copper network, having been adopted by both the European Telecommunications Standards Institute (ETSI) and the International Telecommunications Union (ITU). The first part of this paper provided a technical comparison of the two methods. This second part will provide in both outline and tabular form the generally agreed-upon technical strengths and weaknesses of each.

The following compares specific aspects of CAP and DMT (and a score will be kept regarding what are considered to be significant advantages of one technology over the other):

**Technical:**
• DMT is a *multi-carrier* modulation technique closely related to orthogonal frequency division multiplexing (OFDM). With OFDM having been selected as the modulation technique for digital TV in Australia, Europe and Japan, it is reasonable to assume that over time DMT will benefit from this relationship and also become a well-understood technology (if it isn’t already), just as CAP has benefited from its close relationship to QAM. **Score: CAP 0, DMT 0**

• Many CAP supporters make the claim that DMT, because of it being a multi-carrier modulation technique, is inherently more complicated and therefore more expensive to implement than CAP. Opponents to this claim state that this is no longer true due to continuing advances in IC design and manufacturing processes which now permit the economical implementation in silicon of the digital processing needed by DMT. **Score: DMT 1, CAP 0**

• Each of DMT's 248 (maximum) bins can be independently-modulated up to a maximum of 15 bits/sec/Hz [Baines]. This provides for an optimized SNR per bin, with each bin being able to independently adapt to changing line conditions, crosstalk and interference in certain bandwidths. **Score: DMT 2, CAP 0**

• DMT is particularly well-suited at handling noise resulting from AM radio broadcasts, again due to it being a multi-carrier modulation technique. **Score: DMT 3, CAP 0**

• A single-carrier modulation technique such as CAP (or QAM) works fine in a “clean” channel, where all frequencies are received in the same condition as they were transmitted. Typically, the only signal impairment in a clean channel is attenuation due to transmission distance, and it can be effectively dealt with. An example of a
clean channel transmission is a satellite broadcast, which almost universally will be QAM-modulated. In a clean channel a single carrier modulation technique works fine, with there not being any benefit in dividing the transmission up into subchannels. Unfortunately for an ADSL transmission, however, the primarily copper POTS “local loop” is far from being a “clean” channel [Baines]. Score: DMT 4, CAP 0

- On the phone lines over which ADSL is transmitted, the following common causes all contribute to degrading the transmission:

1. Attenuation due to distance and the presence of POTS loading coils.
2. Attenuation and echoes due to the presence of POTS bridged taps.
3. RF interference from AM radio.
4. RF interference from "ham" radio.
5. Impulse noise from electrical appliances, lightning, or, somewhat ironic, a telephone going off-hook or ringing.

A DMT-modulated ADSL transmission can effectively deal with all of the above causes of signal impairment. The DMT ATU-C continually monitors the channel and adapts each subchannel by bit swapping between adjacent subchannels. Thus, “cleaner” frequency subbands can carry more data bits than impaired ones, and subchannels with extreme signal impairment can be left idle in a worst-case scenario. In other words, the DMT transmitter can proactively cope with detrimental line conditions in an intelligent manner while simultaneously maintaining optimized data rates. It puts the signal power in the frequency subbands where it will be most effectively utilized. A CAP-modulated ADSL transmission, in contrast, can only be
reactive and attempt to counteract the effects of both both signal attenuation and notches at the receiving modem. **Score: DMT 5, CAP 0**

- DMT-modulated ADSL has a lower power spectral density (PSD) than its CAP-modulated counterpart. PSD is the amount of watts that are put into each Hz of bandwidth. Since CAP is less well matched to the line as DMT and is unable to bypass impaired frequency subbands, in order for it to achieve specific data rates it must increase its PSD and “power through” the line impairment(s). This brute-force approach of increasing the output level and transmitting a stronger signal increases power consumption and violates Federal PSD rules for deployable equipment [Baines]. Thus, for equivalent data rates over an equivalent loop, a CAP-modulated ADSL transmission will require more power than a DMT-modulated counterpart. **Score: DMT 6, CAP 0**

- By virtue of its adherence to a standard, DMT-modulated ADSL possesses *spectral compatibility*, whereas CAP-modulated ADSL does not. Spectral compatibility defines how much energy a system can output, which in-turn defines to what extent interference will occur with other systems using the same medium. The ADSL physical medium is predominantly the POTS unshielded copper twisted pair, bundled into binder groups within the local loop. ANSI T1.413 specifies that in the upstream direction, an ADSL transmission must “roll off” at 140 KHz, and downstream transmissions must roll-off at 1.1 MHz. CAP, however, does not adhere to these specifications. CAP-modulated ADSL rolls-off at a maximum 180 KHz upstream and not until 1.5 MHz downstream. The additional 40 KHz that CAP-modulated ADSL uses in the upstream direction fatally interferes with a DMT-modulated downstream
transmission in that overlapping frequency band. As a result, CAP-modulated ADSL cannot be deployed in the same binder group with DMT ADSL [Baines]. And at the high end of downstream transmissions (>1.1 MHz), CAP ADSL causes crosstalk interference with VDSL systems. **Score: DMT 7, CAP 0**

- As previously discussed, the granularity of a DMT-modulated ADSL transmission is 32 Kbps. CAP-modulated transmissions, however, typically have a granularity of 340 Kbps [Goralsky]. In other words, the data rate of a CAP-modulated ADSL transmission can only be controlled approximately *one tenth* as fine as its DMT – modulated counterpart. This technical reality gives DMT-modulated ADSL a huge advantage over CAP for rate adaption and customer service in general. In particular, for ADSL service intended for rural areas or having long reaches (> 18kft), the “coarseness” of a CAP-modulated transmission renders it totally unsuited for consideration [Baines]. In contrast, DMT-modulated ADSL can be incrementally scaled to support a very long reach and can do so smoothly as reach is increased, from >8 Mbps all the way down to 64 Kbps. (A further discussion of this topic is contained in the RADSL section found later in this paper.) **Score: DMT 8, CAP 0.**

- *Adaptive equalizers* are amplifiers that are used to compensate for attenuation and phase error present within the dynamic range of a transmitted signal’s passband frequency. This compensation, known as *adaptive equalization*, is performed by a modem device. The modem must first “learn” the line characteristics, then it amplifies a signal accordingly in order to obtain a flat frequency response. Also, the greater the dynamic range, the more complex adaptive equalization becomes. As would be expected, this increased modem complexity also results in increased modem
cost. Adaptive equalization is required for CAP-modulated ADSL because noise characteristics can vary significantly across the transmitted frequency passband [Abe]. In contrast, DMT-modulated ADSL does not require adaptive equalization because noise characteristics do not vary significantly across any given 4 KHz subband. **Score: DMT 9, CAP 0**

**Marketplace:**

The fact that DMT-modulated ADSL adheres to a standard (ANST T1.413) cannot be overstated; this is a very important fact to consider when one examines compatibility between consumer hardware availability (i.e., the ATU-R), the ATU-C located at the Telco CO, and the modulation method employed by the incumbent local exchange carrier (ILEC). Numerous manufacturers are developing DMT-based hardware: Alcatel, Amati, Analog Devices/Aware, Cisco, Orckit, Motorola, TI, and Pairgain. In contrast, CAP ADSL remains a proprietary single-source technology being developed solely by Paradyne. ("History Repeats Itself" – Recall the proprietary Sony Beta Max video tape format, versus the electronic industry’s standards-based VHS format.) **Score: DMT 10, CAP 0**

- The ITU is considered the ultimate standards body for the telecommunications industry worldwide [Baines]. It recommended in April 2000 to base development of a single worldwide standard for ADSL on ANSI T1.413; or in other words, on a DMT-modulated system. In slang parlance, “the writing’s on the wall” regarding the future of CAP.
• CAP modems (the ATU-R) are inherently more complicated (and therefore expensive) than necessary because they are also designed to demodulate QAM-encoded ADSL transmissions. This dual-mode capability is viewed by many as an example of the uncertainty that exists whenever a product or service does not conform to a universally agreed-upon standard. **Score: DMT 11, CAP 0**

• “Time Marches On” – As of the approximate point in time that this paper was written (Spring, 2001), there is still no CAP-modulated ADSL standard in existence.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>CAP</th>
<th>DMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Compatibility</td>
<td>None – adheres to no standard</td>
<td>Yes – adheres to a specification contained in a standard</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>In theory lower than DMT, but in practice is typically greater due to “brute force” approach when dealing with adverse line conditions</td>
<td>Has a higher peak to average ratio than CAP, but typically requires less power than CAP for like data rates over similar loops</td>
</tr>
<tr>
<td>Echo Control</td>
<td>FDM</td>
<td>Echo Cancellation</td>
</tr>
<tr>
<td># Downstream Channels</td>
<td>1</td>
<td>250 maximum</td>
</tr>
<tr>
<td># Upstream Channels</td>
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<td>32</td>
</tr>
<tr>
<td>Granularity</td>
<td>320 Kbps(^1)</td>
<td>32 Kbps</td>
</tr>
<tr>
<td>Adaptive Equalization</td>
<td>Required</td>
<td>Not required</td>
</tr>
<tr>
<td>Licensing</td>
<td>Globespan</td>
<td>Many sources</td>
</tr>
<tr>
<td>Standardization</td>
<td>In process</td>
<td>ANSI and ITU</td>
</tr>
<tr>
<td>Vendors</td>
<td>Globespan, Paradyne</td>
<td>Many</td>
</tr>
</tbody>
</table>

\(^1\) CAP granularity is generally specified as being 320 Kbps, but it can be less. See the section on rate adaption immediately following for more detail.

The “Rate Adaptive” Controversy

The few vendors who offer CAP-based ADSL products promote what they’ve coined as “RADSL” – an acronym for Rate Adaptive ADSL. Also, when one reads information on CAP-based “RADSL”, one can’t help but notice the marketing “spin” present, where it is implied that DMT-modulated ADSL is not rate adaptive. This implication is completely false and misleading, as DMT ADSL is precisely rate adaptive, having a granularity of 32 Kbps. Initial implementations of CAP ADSL had fixed data rates, and it was not until 1996 that any granularity (340 Kbps) became available.

According to information provided via email on 4/16/01 from Gordon Bremer of Paradyne, the 340 Kbps granularity in not true for CAP ADSL in general. He states that
CAP can operate at any symbol rate, with fractional bits per symbol being possible and practical. The 340 Kbps value is based upon a carrier signal frequency of 340 KHz. Thus, when an integer number of bits per symbol is used, the data rate can vary by only 340 Kbps increments. He also gave the example of Paradyne’s ReachDSL product that operates at 64 KHz. With symbol sizes ranging from 2 to 15 bits, transmission rates from 128 Kbps to 960 Kbps can result, and the granularity is 64 Kbps.
## II. DMT vs. CAP Market Comparison

### Table 5 – ADSL CPE Summary

<table>
<thead>
<tr>
<th>Vendor, Product Name</th>
<th>Device Type</th>
<th>Line Encoding</th>
<th>Max. Speed Upstream</th>
<th>Max. Speed Downstream</th>
<th>Chipset Used</th>
</tr>
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<tbody>
<tr>
<td>3Com HomeConnect</td>
<td>Modem (Dual Link)</td>
<td>DMT</td>
<td>1 Mbps</td>
<td>8 Mbps</td>
<td>Alcatel</td>
</tr>
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<td>3Com HomeConnect</td>
<td>Modem</td>
<td>DMT</td>
<td>1 Mbps</td>
<td>8 Mbps</td>
<td>Alcatel</td>
</tr>
<tr>
<td>3Com HomeConnect</td>
<td>Modem/bridge</td>
<td>DMT</td>
<td>1 Mbps</td>
<td>8 Mbps</td>
<td>ADI</td>
</tr>
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<td>Modem (internal)</td>
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<td>8 Mbps</td>
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</tr>
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<td>8 Mbps</td>
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</tr>
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<td>8 Mbps</td>
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<td>Modem</td>
<td>DMT</td>
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<td>8 Mbps</td>
<td>Alcatel DynaMiTe</td>
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<td>Modem (internal)</td>
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<td>8 Mbps</td>
<td>Alcatel DynaMiTe</td>
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<td></td>
<td></td>
<td>1.1 Mbps</td>
<td>6.2 Mbps</td>
<td>Globespan</td>
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</tr>
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<td>FlowPoint SmartSwitch 250</td>
<td>Router</td>
<td>DMT</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>960 Kbps</td>
<td>8 Mbps</td>
<td>Alcatel DynaMite</td>
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</tr>
<tr>
<td>Fujitsu SPEEDPORT</td>
<td>Modem/Bridge</td>
<td>DMT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>768 Kbps</td>
<td>8.192 Mbps</td>
<td>Orckit</td>
<td></td>
</tr>
<tr>
<td>Hynix HASB-100</td>
<td>Bridge</td>
<td>DMT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 Mbps</td>
<td>10 Mbps</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Hynix HASR-100</td>
<td>Router</td>
<td>DMT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 Mbps</td>
<td>10 Mbps</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Hynix HASP-100</td>
<td>Modem (internal)</td>
<td>DMT</td>
<td></td>
<td></td>
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<tr>
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<td>1 Mbps</td>
<td>10 Mbps</td>
<td>NA</td>
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<td>Modem</td>
<td>DMT</td>
<td></td>
<td></td>
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<td></td>
<td>1 Mbps</td>
<td>10 Mbps</td>
<td>NA</td>
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</tr>
<tr>
<td>Infinilink i510</td>
<td>Router</td>
<td>DMT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>800 Kbps</td>
<td>8.192 Mbps</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Infinilink i500</td>
<td>Bridge/Router</td>
<td>DMT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>640 Kbps</td>
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<td>DMT</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>800 Kbps</td>
<td>8.192 Mbps</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Infinilink</td>
<td>Modem</td>
<td>DMT</td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td></td>
<td>640 Kbps</td>
<td>8.192 Mbps</td>
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</tr>
<tr>
<td>Device</td>
<td>Type</td>
<td>Interface</td>
<td>CAP/DMT</td>
<td>Max Downstream</td>
<td>Max Upstream</td>
</tr>
<tr>
<td>----------------------------</td>
<td>---------------</td>
<td>-----------</td>
<td>---------</td>
<td>---------------</td>
<td>--------------</td>
</tr>
<tr>
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<td>Modem</td>
<td>DMT</td>
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<td>DMT</td>
<td>1 Mbps</td>
<td>8 Mbps</td>
<td>NA</td>
</tr>
<tr>
<td>Intel 2200</td>
<td>Modem (internal)</td>
<td>DMT</td>
<td>1 Mbps</td>
<td>8 Mbps</td>
<td>NA</td>
</tr>
<tr>
<td>Next Level N^2 ETHERSet</td>
<td>Modem</td>
<td>DMT</td>
<td>768 Kbps</td>
<td>8.192 Mbps</td>
<td>NA</td>
</tr>
<tr>
<td>Nokia M1122</td>
<td>Modem</td>
<td>DMT</td>
<td>800 Kbps</td>
<td>1 Mbps</td>
<td>Alcatel</td>
</tr>
<tr>
<td>Nokia M5122</td>
<td>Bridge</td>
<td>DMT</td>
<td>800 Kbps</td>
<td>1 Mbps</td>
<td>Alcatel</td>
</tr>
<tr>
<td>Orckit</td>
<td>Modem</td>
<td>DMT</td>
<td>768 Kbps</td>
<td>8.192 Mbps</td>
<td>NA</td>
</tr>
<tr>
<td>Paradyne Hotwire 5620</td>
<td>Bridge</td>
<td>CAP</td>
<td>1.088 Mbps</td>
<td>7.168 Mbps</td>
<td>Globespan</td>
</tr>
<tr>
<td>Paradyne Hotwire 5446</td>
<td>Router</td>
<td>CAP</td>
<td>1.088 Mbps</td>
<td>7.168 Mbps</td>
<td>Globespan</td>
</tr>
<tr>
<td>Recsol Recspeed 8050E</td>
<td>Modem</td>
<td>DMT</td>
<td>768 Kbps</td>
<td>8.192 Mbps</td>
<td>ST Micro TOSCA/ITEX Apollo A</td>
</tr>
<tr>
<td>Sagem Fast 1000</td>
<td>Modem</td>
<td>DMT</td>
<td>768 Kbps</td>
<td>8.192 Mbps</td>
<td>NA</td>
</tr>
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<td>Sagem Fast 1100</td>
<td>Modem/Bridge</td>
<td>DMT</td>
<td>768 Kbps</td>
<td>8.192 Mbps</td>
<td>NA</td>
</tr>
<tr>
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<td>768 Kbps</td>
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</tr>
<tr>
<td>Sagem Fast 1600</td>
<td>Router</td>
<td>DMT</td>
<td>768 Kbps</td>
<td>8.192 Mbps</td>
<td>NA</td>
</tr>
<tr>
<td>Samsung 320</td>
<td>Modem</td>
<td>DMT</td>
<td>832 Kbps</td>
<td>8 Mbps</td>
<td>ADI 930</td>
</tr>
<tr>
<td>Samsung 335</td>
<td>Router</td>
<td>DMT</td>
<td>832 Kbps</td>
<td>8 Mbps</td>
<td>STM Mascot</td>
</tr>
<tr>
<td>Samsung 215</td>
<td>Modem</td>
<td>DMT</td>
<td>832 Kbps</td>
<td>8 Mbps</td>
<td>Alcatel</td>
</tr>
<tr>
<td>Samsung 500H</td>
<td>Router</td>
<td>DMT</td>
<td>1 Mbps</td>
<td>8 Mbps</td>
<td>NA</td>
</tr>
<tr>
<td>Samsung 525</td>
<td>Modem/Gateway</td>
<td>DMT</td>
<td>640 Kbps</td>
<td>8 Mbps</td>
<td>NA</td>
</tr>
<tr>
<td>Sasken Synaspe G.dmt</td>
<td>Modem (internal)</td>
<td>DMT</td>
<td>640 Kbps</td>
<td>8 Mbps</td>
<td>NA</td>
</tr>
<tr>
<td>Virtual Access 3531</td>
<td>Modem/Gateway</td>
<td>DMT</td>
<td>1 Mbps</td>
<td>8 Mbps</td>
<td>NA</td>
</tr>
<tr>
<td>ZyxXEL Prestige 630</td>
<td>Modem</td>
<td>DMT</td>
<td>1 Mbps</td>
<td>8 Mbps</td>
<td>NA</td>
</tr>
<tr>
<td>ZyxXEL Prestige 642ME</td>
<td>Modem</td>
<td>DMT</td>
<td>832 Kbps</td>
<td>8 Mbps</td>
<td>NA</td>
</tr>
<tr>
<td>ZyxXEL Prestige 642R</td>
<td>Router</td>
<td>DMT</td>
<td>832 Kbps</td>
<td>8 Mbps</td>
<td>NA</td>
</tr>
<tr>
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<td>Bridge</td>
<td>DMT</td>
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<td>8 Mbps</td>
<td>NA</td>
</tr>
<tr>
<td>ZyxXEL Prestige 643</td>
<td>Router</td>
<td>DMT</td>
<td>832 Kbps</td>
<td>8 Mbps</td>
<td>NA</td>
</tr>
</tbody>
</table>

1 All device types are external, unless otherwise indicated.
2 No ADSL over ISDN, G.Lite, or wireless devices are listed.
Table 5 above was compiled from a list of all vendors indicated by the ADSL Forum as being providers of ADSL customer premises equipment (CPE), as of June 2001. For the record, the ADSL Forum has remained neutral regarding endorsing either CAP or DMT as the preferred method of line encoding. The table contains a total of 32 manufactures and 100 CPE device models. A grand total of 10, or 10% of the CPE device total, support CAP line encoding. The remaining 90 CPE devices all supported DMT line encoding, and in particular all specified support of ANSI T1.413 Issue 2, ITU G.992.1 (formerly ITU G.DMT), and ITU G.992.2 (formerly ITU G.Lite). It thus appears that not only have the ADSL CPE manufactures almost unanimously selected DMT as the preferred modulation method, but also have almost unanimously decided to support a variant of ADSL, “ADSL Lite”, or G.Lite. (G.Lite is also standardized by both ANSI and ITU and specifies a maximum downstream rate of 1.6 Mbps and a maximum upstream rate of 512 Kbps, and does not require a POTS splitter at the ATU-R.)

The obviously conclusion that can be drawn is that CAP will never have more than an optional, minority presence in the ADSL marketplace. Also, still lacking an ANSI or ITU standard in 2001, CAP products remain based upon a proprietary technology owned and licensed by Globespan Semiconductor Co.
III. The Existing POTS Physical Layer & ADSL

This section will discuss three aspects of the existing POTS copper-based local loop, which is critical for the availability and performance of ADSL:

A) A review of the physical layer that exists between the Telco CO and the ADSL subscriber.

B) The problems that ADSL must contend with when transmitted over copper-based local loops which have been optimized over the years solely for voice communications.

C) The factors that limit ADSL transmission distances between the CO and subscriber, and in some cases prohibit the offering of ADSL altogether.

III-A) The Physical Layer

The following is the general layout of an ADSL access network based upon a “legacy” analog POTS local loop, and ignores for the time being more recent digital Telco technology such as the digital loop carrier (DLC) and the digital access and cross-connect (DACS) unit:
Overview

**Subscriber Interface**

When a network interface card (NIC) is *not* employed, the most common means of connecting a PC to an external ADSL modem is through standard 10BaseT Ethernet cable. A less common method is the use of ATM-25 cable. And as previously mentioned, the other option is having an internal ADSL modem contained on a NIC within the PC.

**POTS Splitter (SOHO)**

The ADSL modem, either contained internally on a NIC or on the more common external variant, also contains the means by which POTS signals can coexist and remain separated from ADSL signals. A POTS splitter is required at both ends of the ADSL circuit: at the ATU-R located at the small office or home (SOHO), and at the Telco CO. The splitter contains both bidirectional high-pass and low-pass filters. Though ANSI T1.413 specifies that the ADSL splitter cut-off frequencies above 4 KHz, it is common for splitters to
allow frequencies up to 20 KHz to pass. This permits the continued functionality of home alarm systems.

**ATU-R**

The ADSL transceiver unit – remote (ATU-R) resides at the ADSL subscriber’s location, and is in effect the ADSL modem or CPE. It can be external, internal on a NIC, or as part of a router for a SOHO network. The ATU-R receives high-data rate downstream ADSL transmissions and transmits lower-data rate ADSL transmissions upstream. It also contains the POTS splitter, separating POTS from ADSL transmissions.

**The “Twisted Pair”**

By far the most common form of wiring making up the “local loop” are unshielded twisted pairs (UTP) of copper wire between the subscriber and Telco CO. In general, the maximum length that a local loop can be and still qualify for supporting ADSL transmissions over it is 18,000 feet, or approximately 3.4 miles. Since ADSL data rates vary inversely with local loop length, the latter dictates the former.

**POTS Splitter (CO)**

The POTS splitter at the Telco CO is the means by which voice calls are sent to the public switched telephone network (PSTN), and ADSL data over to the DSLAM, where it is typically passed via ATM to the Internet. The POTS splitter at the CO may either be a separate device, or it can be contained in the ATU-C.
**ATU-C**

The ADSL transceiver unit – central (ATU-C) is the counterpart to the ATU-R and resides at the Telco CO in the form of a line card. A typical setup will find numerous ATU-C cards plugged into an access shelf. An ATU-C can contain either a single or multiple modems on it, and multiple ATU-C’s can distribute modem functions between them. However, an ATU-C is physically connected to only one ATU-R at a time. The ATU-C may also provide splitter functionality.

**DSLAM**

Located at the Telco CO is the digital subscriber line access multiplexer (DSLAM), which is used to combine numerous individual ADSL connections into a single, high-speed connection, which is then typically sent to an asynchronous transfer mode (ATM) switch. Other popular options include sending the multiplexed ADSL connections to either a TCP/IP router or frame relay switch.

**The Backbone/WAN Cloud**

A network backbone must exist in order to link the ADSL subscriber to network services. ATM is typically the underlying means of transport used to access the backbone/WAN, though other protocols may be used, such as TCP/IP and frame relay (FR).
The Twisted Copper Pair Environment

In general, for high-speed data transmission a twisted copper pair circuit is noisy, lossy, and susceptible to cross talk [Rauschmayer]. It is the responsibility of the line encoding used to overcome these impairments in order to make the use of existing local loops feasible and practical for high-speed ADSL data transmission.

The DSLAM

The digital subscriber line access multiplexer (DSLAM), typically located in the ILEC’s CO, is the interface device through which information enters and leaves the numerous ATU-Cs. It is the link between the DSL subscribers located on the local loops and the Internet, corporate/educational networks, WWW, etc. All traffic to/from users and to/from what is behind it goes through the DSLAM. Because of the need for local loop access, DSLAMs are usually located in the wire center of the CO. However, with the increased deployment of Digital Loop Carriers (DLCs) by LECs, it is becoming common practice to locate the DSLAM with the Remote Terminal (RT) of a DLC’s Carrier Serving Area (CSA) (discussed below).

In this discussion the DSLAM will be studied from an ADSL perspective, though it is present in all DSL applications (HDSL, SDSL, IDSL, VDSL, etc.). In the terminology of ANSI T1.413, the DSLAM fulfills the role of the ADSL access node. If reference is made to the ADSL Forum’s ADSL Reference Model, the DSLAM interfaces with content providers through the A4 interface, and with ADSL subscribers through the A2 interface [ADSL Forum]. The DSLAM is a versatile device, typically containing the ATU-C
splitter for POTS as well as the ability to interface with TCP/IP routers, ATM switches, frame relay switches, LANs, and numerous other broadband services. Its location in a generalized ADSL network model is that of the network access provider (NAP), situated between the service user (SU) and network service provider (NSP) portions of the network model. The NSP and NAP (the DSLAM) are connected by an access network, which can vary in complexity ranging from a lone ATM switch, IP router, or frame relay high-speed serial interface (HSSI), to a full-fledged network.

The basic DSLAM is best described as being a multiplexer, rather than a switch or router. The DSLAM combines bit streams coming from upstream SOHO subscribers and segments by channel to subscribers a downstream bit stream, typically coming from an ATM or IP network. As a result, the Telco trunks between the DSLAM and local loops must have the capacity to carry the sum total of all upstream traffic simultaneously [Goralski]. This traffic management is accomplished by using time division multiplexing (TDM). Due to the “bursty” nature of the majority of Internet and WAN traffic, statistical TDM is also employed by DSLAMs. The following summarizes the primary functions of an ADSL DSLAM:

- Contain the ATU-C interfaces (one per subscriber)
- Multiplex upstream traffic coming from these ATU-Cs onto a high-speed trunk to the access network
- Demultiplex downstream traffic coming from the access network and assign it to the correct ATU-Cs
- “Supervises” line speed negotiation between the ATU-C and ATU-R
• Act as a central management platform
• Terminate ATM traffic from the access network and convert to IP where required by the subscriber’s ATU-R
• “Supervises” the latency path selection of each ATU-C for both fast and interleaved data frames

Also, most vendor’s ADSL DSLAMs usually support the following:

• *Rate adaptive* DSL (RADSL)*
• Either CAP or DMT line encoding, and sometimes both
• ATM, 10BaseT and 100BaseT Ethernet access network connections
• ATM and IP network protocols
• *Simple Network Management Protocol* (SNMP)

The number of local loops served by a DSLAM can range from less than 100 to more than 1000. A *printed circuit* (PC) card for each local loop served contains the necessary software and hardware for the ADSL line code in use (CAP or DMT). The PC cards are installed into one or more shelves, which in-turn are contained in a rack. If a particular DSLAM is also going to support multiple types of DSLs, this capability is provided by the functionality of the PC cards installed. The access network connection types can be ATM (usually over a 155 Mbps *Synchronous Optical Network* (SONET) OC-3 line), 10 or 100 Mbps Ethernet, frame relay, or T-carrier circuits. Some DSLAMs may also perform bridging and routing functions, and receive ATM cells and IP packets directly.

In addition to ATM, IP, and FR, other supported networking protocols include Novell’s
Internetwork Packet Exchange (IPX) and Sequenced Packet Exchange (SPX), Internet point-to-point protocol (PPP), DOS and Windows’ NetBIOS, and IBM’s Synchronous Datalink Control (SDLC). For network management functions, Common Management Interface Protocol (CMIP) is supported in addition to SNMP.

The functionality of DSLAMs is changing as DSLs proliferate. A good example of this can be found where the DSLAM already contains IP routing capability internally, eliminating the need for both a separate external Ethernet hub and IP router, along with their associated cabling. Similarly, where a DSLAM will be required to support ATM networking protocol, the DSLAM can contain an ATM switch internally. And in cases where the ADSL provider connects to a frame relay access network, the DSLAM can also contain FR switching internally.

POTS Local Loops

Initially, POTS local loops consisted of a single, bare copper wire going to each telephone set and utilized a ground return. It was later discovered that providing a metallic return by the addition of a second, bare copper wire reduced crosstalk, and thereby significantly improved the quality of voice conversations. Unfortunately, though now fairly immune to crosstalk, these long runs of parallel and un-insulated copper wires had a capacitive effect, which in-turn caused signal attenuation and a “muffled” sounding voice at the receiver. It was next discovered (by Alexander Graham Bell himself, in 1881) that by twisting the wire pairs together in a helical pattern, the amount of signal attenuation was reduced. This was due to an electrical property known as mutual
inductance, which cancelled-out some of the capacitance of the wires. Finally, the use of shielded or insulated copper wire pairs was contemplated, but it was determined to be too costly and also increased signal attenuation [Goralsky].

The evolution of telephone wires up to this point resulted in what has since been referred to as the unshielded twisted pair, also abbreviated simply UTP. After considerable trial and effort, the Telco's established that UTP of either 19, 22, or 24 AWG (American Wire Gauge) in size could be used to wire local loops a maximum of 18,000 feet in length. If a local loop exceeded this 18 kft maximum, voice quality would again become muffled due to the attenuation-reducing effect of induction, which resulted from the twisting of each wire pair, having reached its maximum level and no longer being effective. In order to extend local loops beyond 18kft, the addition of more inductance was needed. This was accomplished by the use of loading coils.

Each POTS subscriber’s UTP local loop is bundled together with other subscriber’s UTPs into a cable known as a binder group. Binder groups are segmented into 500 foot sections, which are spliced together as needed in order to reach each subscriber from the CO. A typical binder group contains 50 UTPs, but the number can range from as low as 20 UTPs to as many as a few hundred. Coming out of the CO for approximately the first 9000 feet are feeder cables, which are larger binder groups containing hundreds or thousands of bundled UTPs. Regardless of UTP quantity, the wire size is 26 AWG leaving the CO out to 10 kft, and then increases to 24, 22, or 19 AWG from there on [Abe].
### Table 6 – UTP Copper Wire Specifications

<table>
<thead>
<tr>
<th>AWG Size</th>
<th>Diameter (inch/mm)</th>
<th>Resistance @ 77°F (Ω/kft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>0.036/0.91</td>
<td>8.21</td>
</tr>
<tr>
<td>22</td>
<td>0.025/0.64</td>
<td>16.5</td>
</tr>
<tr>
<td>24</td>
<td>0.020/0.51</td>
<td>26.2</td>
</tr>
<tr>
<td>26</td>
<td>0.016/0.41</td>
<td>41.6</td>
</tr>
</tbody>
</table>

**Loading Coils**

The use of *loading coils*, resulting in *loaded local loops*, provided the added inductance required to exceed 18 kft lengths and still maintain acceptable voice quality. By carefully adding inductance to a circuit, a specific bandwidth range can be “tuned” so that the received power of a transmitted signal can be increased, overcoming the signal loss originally caused by attenuation. For an analog POTS local loop, this bandwidth range is between 300 and 3,300 Hz. There are three loading schemes in use today: B-44, D-66, and H-88.

Since loading involves adding inductance, the unit of measured used is the *millihenry* (*mH*). Loading coils are made of iron and shaped like a doughnut, around which each wire of the loop’s UTP is wrapped. For ease of Telco installation, all UTPs within a binder group are loaded, even if not all individual UTPs require the added inductance [Abe]. The amount of inductance added to an analog local loop is determined by both the inductance characteristics of the loading coils used and the spacing between them. Table 7 summarizes loading coil specifications:
Table 7 – Loading Coils

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Inductance (mH)</th>
<th>Line Spacing (ft)</th>
<th>Max. Freq. (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-44</td>
<td>44</td>
<td>3,000</td>
<td>3150</td>
</tr>
<tr>
<td>D-66</td>
<td>66</td>
<td>4,500</td>
<td>4300</td>
</tr>
<tr>
<td>H-88</td>
<td>88</td>
<td>6,000</td>
<td>5300</td>
</tr>
</tbody>
</table>

Two important points need to be noted about loading coils:

1. The maximum distance that loading can extend an analog local loop is up to 30 kft (approx. 5.7 miles).

2. Regardless of the loading scheme used, a loaded local loop will have a basically flat (i.e., constant) signal loss profile, plotted as attenuation (dB/mile) versus frequency (KHz), within its intended frequency range. This is the desired result for voice transmission. However, above each scheme’s maximum frequency, attenuation increases rapidly and exceeds that which would be present on a non-loaded loop of identical construction.

**Bridged Taps**

Bridged (or bridging) taps are extra UTPs that are spliced or “tap” into an existing UTP for the purpose of connecting to another possible device (i.e., analog telephone). Their presence allows the Telco flexibility in field installations and can be up to 5 kft in length themselves. A typical example of a bridged tap installation is when a Telco is wiring a new local loop to a new housing tract. Not all the homes are built at once, yet the POTS wiring (along with the utility, water and sewer) infrastructure needs to be in place. The local loop is put in place and is of a specific length. However, as new homes are constructed that are located within the reach of the local loop, a specific UTP bundled
within the binder group of the newly installed local loop is simply spliced or “tapped” into. The original UTP that has been tapped into would also typically not be terminated at the location of the bridged tap, but would continue on as originally installed.

The presence of bridged taps introduces the potential for two types of problems:
1. Signals can echo, or be reflected back to their source, by the presence of the splice.
2. The unterminated portion can behave as an antenna and be the cause of signal leakage, which, in turn, causes a loss of signal strength.

The 'Y' junction that exists at the tap has no effect on low frequency signals such as POTS, but causes problems with high frequency transmissions. When an ADSL signal encounters the branching point, the signal travels down both branches of the 'Y' and is reflected back to the other branch, causing multiple echoes. Echo cancellation is effective when a reflection is from a single source, but looses its effectiveness when there are multiple sources of echoes [Abe]. And at the branch of the 'Y' that is left un-terminated, abnormal attenuation of the desired signal will result. On local loops that contain multiple bridged taps, their adverse effects are cumulative.

One additional purpose served by bridged taps was the offering of party line local exchange telephone service. In years past, LEC’s offered POTS where multiple subscribers would share the same phone number. As it could be imagined, if one member of the “party” were carrying on a telephone conversation, another member had to wait until this current call was concluded before a new call could be placed.
**Line Extenders**

Line extenders are signal amplifiers and are another means used to extend the reach of a local loop. They are non-standard devices and are proprietary to the ILEC or RBOC employing them, and their presence requires that CPE such as telephones, fax machines, and dial-up modems are compatible with the device. Line extenders can increase the reach of a local loop out to 25 kft (approx. 4.7 miles).

**Mixed Wire Gauges**

The presence of mixed sizes of UTP in a POTS local loop is not at all uncommon. In fact, if we go back to where binder groups and feeder cables were discussed, it is a standard Telco practice. As table 6 points out, the resistance of the wire contained in the UTP changes as the diameter of the copper wire changes. However, in practice the presence of mixed sizes of UTP has proven not to be troublesome for analog voice transmissions within 0 – 4 KHz spectrum.

The reason Telco’s use the smallest size wire possible in a local loop is simple – cost. It is estimated that local loops account for roughly half of a Telco’s capital costs [Abe]. And since U.S. Telcos are the largest single-source consumer of copper in the world, one way in which to control these capital costs is by using the least amount of copper wire possible, and still provide acceptable service. This is evident by the typical local loop design where UTP containing 26 AWG wiring is used from the CO out to 10 kft, then increasing to 24 AWG out to 18 kft. Where local loop lengths exceed 18 kft, such as rural areas served by loaded loops, 19 AWG is used in the final segments.
**Digitization of POTS**

Integrated Services Digital Network (ISDN) was derived by AT&T Bell Labs as the complete end-to-end digitization of the telephone network. In particular, it digitized the last segment of the PSTN, the local loop. ISDN never really caught on, and for a number of well-documented reasons. What was to occur on a large scale, however, was the digitization of the trunk lines that connected local loops to the CO, with the local loop remaining analog.

Telco central offices are expensive to both construct and maintain. In post-WW2 America began both the explosive growth of suburbia and the mass migration of people exiting the NE for the SE and western states, which still continues till this day. This change in demographics provided the Telcos with the impetus to find lower-cost alternatives to supplement, if not replace, the CO. Also, in already established suburban areas that were experiencing continual growth, the need arose to keep existing binder groups from becoming unwieldy [Abe]. The answer to this problem was the digital loop carrier (DLC), developed in the 1980s by AT&T and its then-subsidiary Bellcore. The DLC represented a distributed architecture between the CO and subscriber, and had three “motivators” behind it:

1. Reduce the load placed on existing PSTN switches by new subscribers;
2. Reduce the number of new COs required;
3. Place switching equipment closer to the subscriber.
In its most basic description, a DLC is a digital trunk between the CO and a remote terminal (RT), which is located within a carrier serving area (CSA). T1 carriers are used to digitize 10 UTPs between the CO and RT, with 2 UTPs required for each T1 line. Voice traffic is assigned to 24 channel time division multiplexing (TDM) per pair of UTP. Of the 10 UTPs, 8 carry multiplex voice traffic, resulting in a total of 96 voice channels (4 x 24). The remaining pair of UTP is used for call signaling and network management purposes. At the CO, a central office terminal (COT) provides the interface to the individual ports of the PSTN switch, while in the field the RT connects 96 individual analog UTP loops to subscribers located in the CSA. RTs can be located on telephone poles and in pedestals, vaults, and office buildings. The maximum loop distances from the RT are 12 kft for 24 AWG UTP and 9 kft for 26 AWG UTP.

The most obvious benefit here is the significant reduction in the amount of copper wire required. For example, what was just described was Lucent’s Subscriber Loop Carrier – 96 (SLC-96) system. With SLC-96, the 96 UTPs terminate remotely in the RT, as opposed to the CO. From the RT, 10 UTPs carry digitized and multiplexed voice traffic back to the CO over five T1 (four active, one spare) circuits. This combination of five T1 circuits is in actuality a T2 line and one spare T1 line. The net result of this is that 10, not 96, UTPs are needed between the CO and RT. This net reduction in the number of UTPs needed is referred to in the Telco industry as pair gain.

More recent DLC installations use fiber optic cable between the CO and RT, with an example of such being Lucent’s SLC-2000 system. It also common to install RTs in
controlled environmental vaults (CEVs), which can be either underground or above-ground pedestals. A CEV can also switch calls whose origin and destination are within the same CSA, thus relieving the CO of the function.

**III-B) ADSL Problems and the Local Loop**

The copper UTP-based POTS local loop has served the purpose of delivering analog voice transmissions reliably and quite adequately for over 100 years. Since the infrastructure's sole purpose for so long was to support POTS, maintenance and delivery techniques were developed and optimized to support this sole function. In a similar manner, technical innovations which addressed impairments to voice transmissions were implemented throughout the years. The following summarizes the problems that ADSL service will experience due to this optimization of the local loop for passband analog voice traffic:

- All frequencies above a nominal 4 KHz are filtered out by the presence of *loading coils*.
- High frequency signals also experience severe attenuation and reflection due to the presence of *bridged taps*.
- Echoes are also created on digital circuits due to signal reflections coming from *mixed UTP sizes*.
- The *remote terminal* (RT) located in a *carrier serving area* (CSA) limits the bandwidth available on all local loops serviced to 4 KHz (64 KHz for digital local loops).
All frequencies above a nominal 4 KHz can be subjected to narrowband interference from sources such as AM and "ham" radio broadcasts.

The copper wires themselves contained within the UTP binder group, even when of a uniform diameter throughout the length of a local loop, can be the cause of a number of additional problems when used for carrying high-frequency transmissions:

- The simple fact of the matter is that signal loss or attenuation increases with frequency. The distance a signal can travel over metallic wires decreases by the square of the frequency [Abe]. Signal attenuation also increases with the length of the circuit and as the temperature of the copper wire increases.

- Electromagnetic coupling between adjacent UTPs bundled together in a binder group is the source of unwanted crosstalk. And again, as the signal frequency increases, the amount of crosstalk increases.

- A phenomenon known as skin effect occurs when high frequency signals are transmitted over metallic wires [Abe]. The electricity flowing through the wires migrates to the outer circumference of the wire, in effect creating an area of low conductivity near the center of the wire. Since less cross-sectional area of the wire is now being used to conduct electricity, resistance in the wire increases and we now have another cause of signal attenuation. Because of skin effect phenomenon, the maximum signal frequency transmitted over metallic wired media is approx. 1 GHz.

- The velocity of a transmitted signal also decreases as the signal’s frequency increases. This slow-down causes a phase error, which can cause bit errors when a phase modulation of a signal is performed (such as with CAP).
One other condition can exist within a POTS binder group that can prevent ADSL from being supported. ADSL cannot coexist in the same binder group if one or more leased T-1 lines are present that are encoded by the *Alternate Mark Inversion* (AMI) modulation scheme. The problem stems from the fact that AMI uses a lot of bandwidth – in excess of 1.0 MHz. Since DMT ADSL occupies basically the same frequency spectrum, the two cannot coexist. It should be noted, however, that ADSL is designed to coexist in the same binder group with both ISDN and T-1 lines encoded by modulation schemes other than AMI. Specifically, ADSL is designed for 6 Mbps within a 9 kft CSA of 26 AWG UTP when in the presence of ISDN and/or non-AMI encoded T-1 service [Abe].

Finally, ADSL can coexist with ISDN on the same line. However, with ISDN being a digital baseband service, it uses up more bandwidth that’s available over the UTP. Specifically, ISDN operates in the 26 KHz – 140 KHz frequency spectrum. This results in the ADSL service over the same line having reduced bandwidth available to it. And unfortunately for ADSL, this low-frequency bandwidth is where DMT ADSL can really “pack it in” and maximize the number of bits per bin or frequency tone. Since upstream bandwidth for ADSL is defined as the 30 KHz to 138 KHz range, it is completely displaced by the presence of ISDN, and must now share bandwidth with downstream traffic by means of echo cancellation in the 150 KHz to 260 KHz range.
III-C) ADSL Availability and the Local Loop

Specifications exist regarding the maximum distances subscribers can be located from either a CO or an RT if served by a CSA. If connected directly to a CO, the following specifications, known as revised resistance design rules (RRD) apply:

- 18 kft for 24 AWG UTP
- 15 kft for 26 AWG UTP

From remote terminal, the maximum length of a CSA can be as follows:

- 12 kft for 24 AWG UTP
- 9 kft for 26 AWG UTP

It is also of interest to note that the CSA rules prohibit the installation of loading coils altogether, and impose restrictions on the use of bridged taps. This probably was due to the expectations that ISDN once held. Within a CSA, the total length of all bridged taps cannot exceed 2,500 ft, and the maximum length of any individual bridged tap cannot exceed 2,000 ft.

Estimates for the U.S. for the year 2000 indicate that approximately 50% of all local loops were located within 9000 feet of either a CO or RT of a DLC system, and 80% were within 15,000 feet of either. Also, approximately 20% of all local loops were connected to a DLC system. Local loops having loading coils installed is also estimated to be on the order of 20%. However, it is interesting to note that this figure is believed to be significantly higher for the ILEC in the Rochester area, Frontier/Citizens Communication Company. In the 1970’s (as Rochester Telephone Corp.), loading coils were installed as standard practice on all new local loops, regardless of length.1
The over-all average length of all local loops in the U.S. is 11,000 ft. Since the standard length of a binder group is a 500 ft section, this results in there being 22 splices on average in each local loop. Each splice provides a potential location for corrosion to develop, as well as being the recipient of poor workmanship. In both cases signal attenuation will result.

The first, and most basic requirement for a local loop to be qualified to provide ANSI-standard ADSL service is that there are no loading coils present. As previously discussed, loading coils block all frequencies above the nominal 4 KHz used by POTS and therefore would prohibit ADSL service. The second basic requirement is that loop length be a maximum of 18,000 feet in length in order to provide the maximum data rates of 8 Mbps downstream and 800 Kbps upstream. The third basic requirement is that only one bridged tap is present per UTP pair, and it is used to provide POTS to the SOHO subscriber’s premises. One estimate currently puts as high as 85% the amount of local loops that meet the 18 kft length and single bridged tap requirements, and this number will increase as more DLCs are put in place. (Note that non-ANSI ADSL offerings such as Lucent’s DMT-encoded "Wildwire", Nortel’s QAM-encoded "1-Meg Modem", and Paradyne’s CAP-encoded ReachDSL™ advertise greater distances, but at data rates less than maximum ANSI specifications.) Finally, binder groups also must be free of any "hostile" AMI-encoded T-1 traffic.
For the Rochester-area ILEC, Frontier/Citizens Communication Company, there exists an additional incentive to remove loading coils from existing local loops. An incentive regulatory program known as the Open Market Plan (OMP), was imposed upon Frontier by the New York State Public Service Commission for a seven year period starting in 1995. The primary goal of the OMP was to foster competition in the telecommunications marketplace served by Frontier, with the public being the beneficiary of rate reductions and new and improved service offerings. In exchange for its compliance with the plan, Frontier would benefit by a relaxing of rate-of-return regulations and the waiving of an earnings cap.

One of the areas in which the OMP attempted to foster competition was in the broadband data communications marketplace. To be more specific, one of its objectives was to facilitate the availability of DSL service in the area served by Frontier in order to provide an alternative to Time Warner Communication’s “Road Runner” cable modem service offering. Since loading coils must be removed from local loops in order to transmit any frequency above 4 KHz, one of the terms specified by the OMP was for Frontier to “…meet a prescribed schedule for removing load coils on circuits where they are not needed for voice transmission reasons” [NYS PSC]. Granted, Frontier was also required to allow competitors to enter its potential DSL market, but by qualifying its local loops for DSL service (primarily by removing loading coils), Frontier not only became able to offer the service itself but also benefited from the terms of the OMP.
Where subscribers are served by a CSA, the RT is connected to the CO by a DLC feeder trunk, over which up to 96 individual voice channels are digitized and multiplexed together. The problem that such pairgain systems pose for ADSL is that the bandwidth allotted for each channel over the feeder trunks is limited to 64 KHz per channel, well short of the 1.1 MHz required for ADSL. There are two actions needed in order to support ADSL:

1. Locate the DSLAM remotely in the RT of each CSA. This requires that the RT cabinet contains space to house the remote DSLAM, as well as being able to provide power, battery backup, and proper heat dissipation capability.

2. Dedicate a separate trunk from the RT to the CO to carry ADSL traffic between each CSA and the access network. Since a DLC is a pairgain system, idle UTPs within binder groups should be available for the use.
IV. Splitterless G.Lite

A fundamental requirement of ADSL is the need to separate or "split off" the 4 KHz analog POTS channel from the total 1.1 MHz transmission spectrum used at both the SOHO and CO locations. This task was initially accomplished at these locations by devices known as "splitters" contained in the ATU-R and ATU-C, respectively. This device was in essence a high pass/low pass filtering system that kept voice and data traffic separate from each other. The splitter performs two basic functions:

1. Enables analog telephones and fax machines to coexist with ADSL at the SOHO location

2. It permits ADSL data traffic to bypass the PSTN switch at the CO, in contrast to dial-up modems, which add to switch congestion and circuit contention.

Unfortunately, however, professional installation of the POTS splitter at the SOHO location by a Telco service technician was required. This was to ensure that no analog phone was connected to the wiring portion that existed between the ATU-R and the ATU-C located at the CO or RT. Therefore, for full-rate ADSL, the location of the splitter was critical and the installation of new wiring dedicated to data use might be required.
However, this need for professional installation of the splitter at the SOHO locations posed a number of concerns as far as the service provider was concerned:

- It required the need for a scheduled service call to the customer’s premises in order to install the splitter and make any necessary wiring changes. This was viewed as being an inconvenience for both the service provider and the customer.

- The need for a service technician to be on-site to perform an installation also was seen as adding cost to the roll-out of the ADSL service. The cost of labor had to be accounted for, as well as the splitter. These costs were obviously passed-on to the customer as an installation fee.

- The need for service technicians to perform the SOHO installations raised concerns regarding mandated Quality-of-Service (QOS) standards for telephone service and put an added demand on service and repair organizations whose size had been determined by years of solely performing POTS installation and service.
As a result of these issues, elimination of the POTS splitter at the SOHO location and permitting end-user installation as a result was an appealing idea to ADSL service providers.

In addition to the service providers, manufacturers of ADSL hardware also had a vested interest in methods that would simplify and accelerate the roll-out of ADSL. These equipment vendors had invested heavily in the technology and were ready to begin earning an ROI. Nortel and Lucent, who between them provide an estimated 85% of all CO switching equipment in the U.S., took the lead. Both vendors announced the availability of new CO and RT subscriber line cards: Nortel's "1-Meg Modem" and Lucent's "Wildwire". Both of these products contained built-in ADSL modems and were also splitterless. These two features eliminated the need for any wiring or other modifications having to be made at the Telco CO or DLC RT in order to support ADSL. Both vendor's products were also backwards-compatible with existing CO and DLC equipment, which was also an attractive feature to POTS service providers.

Momentum increased in early 1998 for the availability of an "easy-to-install" ADSL. A group including the likes of Microsoft, Intel, and a number of RBOCs announced the formation of the Universal ADSL Working Group (UAWG). The goal of the UAWG was to submit to both ANSI and the ITU a splitterless ADSL solution having data rates 1 to 1.5 Mbps downstream and 100 to 200 Kbps upstream. The result of their efforts was G.Lite, a subset of ANSI T1.413 and ITU G.DMT (now ANSI T1.413 Issue 2/ITU G.992.2).
G.Lite is modulated by a “scaled back” version of DMT and in actuality has maximum transmission rates of 1.512 Mbps downstream and 512 Kbps upstream. Frequency subchannels which are 4.3125 KHz wide are still used, but only up to bin #128 (or half of the 256 subchannels used by full-rate ADSL). As with full-rate DMT ADSL, subchannels 7 – 38, which yield an approximate 26 to 164 KHz wide frequency range, are used for upstream transmissions. Downstream, however, uses only subchannels 39 – 128, giving an approximately 164 to 552 KHz wide frequency range. Frequency division multiplexing (FDM) is used to separate the upstream and downstream paths.

Since G.Lite uses half the number of subchannels as full-rate ADSL, it also requires less power than full-rate ADSL to operate. This makes G.Lite particularly attractive for use in CSAs served by DLCs. Since the DSLAM must be located at the RT of a DLC, it requires power and must be able to dissipate heat build-up. Providing for these capabilities (along with the provision of back-up battery power) has at times added difficulty to offering full-rate ADSL over DLCs. This reduction in power consumption compared to full-rate ADSL should facilitate the placement of G.Lite equipment into the RTs of CSAs.

The key to G.Lite being able to support POTS without the use of a splitter lies in the fast-retrain procedure. When the ATU-R detects that an analog handset has gone off-hook for either a voice call or fax transmission, it reduces (or retrain) the power available for modulating an upstream ADSL transmission. This procedure is to prevent any
interference from occurring with the analog transmission by an upstream digital transmission, if a transmission is in progress. The signal processing techniques that perform "retraining" are performed by a Digital Signal Processor (DSP) contained within the ATU-R modem. When the modem has detected that the analog call has been completed (i.e., gone on-hook), it retrains itself back to maximum transmit power.

A G.Lite ATU-R device also contains a high pass filter internally; thus it's still present but no longer part of the splitter. Also, a microfilter can be installed if necessary by the customer on phones requiring added isolation between POTS and G.Lite service. The microfilter is an in-line low pass filter which blocks any undesired modulated high band signal that was generated at the handset from reaching the ATU-R modem. In summary:

- The high pass filter contained in the POTS splitter for full-rate ADSL in now contained in the ATU-R G.Lite modem.
- The function of the low pass filter, also contained in the POTS splitter for full-rate ADSL, is accomplished by the combination of using reduced power levels for G.Lite transmissions (and hence the reduced data rates) and by retraining. Also, if needed, added isolation can be achieved by the use of a microfilter.

Eliminating the need for a voice-data splitter and the new line between it and the modem has a profound benefit for the end-user. This permits any phone jack in the customer's premises to be used for ADSL access, not just the one provisioned from the splitter. In particular, this would appear to have great potential where many people possessing laptop PCs are gathered, especially when traveling away from home. G.Lite can be accessed
from hotel rooms, convention floors, trade shows, and dorm rooms, with the only requirement being that the user can establish a connection with their ISP.
V. Conclusion

The obvious conclusion that can be drawn from the information contained in this paper is twofold:

1. DMT line encoding is the technically superior technology over CAP for the purpose of modulating ADSL transmissions over POTS local loops and trunk lines.

2. The CPE hardware manufacturers recognize DMT’s superior technology and standardization by virtue of the overwhelming percentage of hardware containing DMT chipsets as opposed to CAP chipsets.

DMT conforms to a standard, ANSI T1.413, and thereby hardware interoperability is assured. It is highly granular and inherently rate-adaptive. What appears to be most appealing from a technological perspective is its ability to optimize modulation by packing the most bits into subchannels having the highest SNRs, and in contrast being able to leave completely idle any subchannels that have serious transmission impairments. Even though a POTS channel’s physical characteristics can vary greatly, DMT possesses the ability to maintain maximum spectral efficiency over the channel. In conclusion, DMT is a standardized, efficient, versatile, flexible and adaptable technology for modulating digital data over copper lines and at high speeds.

The following is an email reply dated 11/20/01 from Chuck Parshall, Jr., Director of Product Management for DSL/Internet/IP Applications at Frontier/Citizens Communication Company here in Rochester. Being an industry professional, I asked him
a number of questions whose answers would (hopefully) substantiate the two points I made in my conclusion above:

Q1: Why was DMT line encoding chosen over CAP by Frontier for its LightningLink physical layer?
A1: "At the time DMT was the "second generation" of DSL technology and in the combat akin to VHS vs. BETA, we felt DMT would win out. Pretty simple; decision point was more a matter of technology growth opportunity than technology performance. Time has proven us correct. The G.Lite interim standard has not been broadly adopted because of its speed limitations and CAP is all but extinct at this point. CAP based providers are currently being forced in many cases to consider a forklift replacement of hardware because scalability has collapsed and the equipment required to grow is becoming scarce."

Q2: ANSI T1.413 specifies a maximum DMT ADSL downstream data rate in excess of 8 Mbps over 18,000 feet for a qualified line, yet LightningLink advertises only 3 Mbps max., and I don't believe a distance is specified. Why the significant reduction in data rate?
A2: "The commodity Internet runs at roughly 700kbps, give or take. Unless a provider is running a lot on on-net only applications, anything above that is essentially unused, since that represents the "weakest Link" in the chain. From an economic standpoint, assigning full rate ATM PVC's would be less than optimal use of the network because, even though the PVC's are only partially used, the entire ATM PVC is committed at that rate. Make for a lot of wasted bit path."

Q3: Regarding your "First Strike" product, is it technically ADSL or G.Lite?
A3: "DMT ADSL, same as LightningLink."

Q4: What is your SDSL product called?
A4: "Frontier Business DSL"

Q5: Presuming your SDSL offering provides a symmetrical 1.544 Mbps data rate, what are its advantages over simply leasing a T-1 line from Frontier?
A5: "Customers recognize the price as being most significant... SDSL provides the speed, depending on distance, of a T-carrier system but at a significant price advantage. Advantages of SDSL include the similar technical performance (from an application perspective) of T-carrier, 2-wire copper vs. 4-wire (lower loop costs). But, the application really determines the difference. Since Business DSL is a modem protocol, is oversubscribed, and network monitoring is not as active as on the T-Carrier systems, most mission critical applications should still be hosted via T-carrier. T-carrier offers the best reach, highest reliability, lower
failure rates (Channelized TDM vs. modem protocol), and more flexibility for larger applications (ATM based T's are highly flexible)."

Q6: Is the inherent rate-adaptive capability of DMT-modulated ADSL being marketed, where data rates over 3 Mbps can be obtained by a SOHO user but at increased cost?

A6: "Frontier has elected to establish data rates within the network as opposed to at the CPE. It lowers costs and increases flexibility in maintenance and monitoring. We do this at the DSLAM port. The rate adaptivity of DMT actually causes problems for us because while it adapts downward in speed, searching for optimal performance, as loop characteristics change over time (seasonality), it is unable to adapt back upward. Since most customers leave their modem powered up, it never has an opportunity to recycle power and retrain back to the higher speeds... We take quite a few calls from customer who tell us their service is "slowing down"... This is typically the cause."

His first answer fully supports the conclusions that when compared to CAP, DMT is by far the superior method of line encoding and the unanimous industry choice.

I need to go no further than Mr. Parshall’s reference to the Beta versus VHS comparison (which I also made on page 45) and his statement that CAP was “all but extinct”, to illustrate this.

His answer to my questioning the discrepancy between LightningLink’s 3Mbps maximum data rate and that specified by ANSI T1.413 was a complete surprise to me. I never came across such information regarding permanent virtual circuits (PVCs) from my research regarding the network backbone and DSLAMs. In contrast to a switched virtual circuit (SVC), a PVC remains permanently available, even after data has been sent. This property makes a PVC more efficient for connecting between hosts or servers that communicate frequently, and are commonly found in ATM and frame relay networks.
I also gained insight not previously acquired via my research from his answer to my SDSL versus T-1 question. Particularly of interest was the trade-off of similar performance and lower loop cost with SDSL versus greater reach and higher reliability with a leased T-1 line.

Finally, his comments on DMT’s rate adaptive capability were also most informative. In particular, the point that adaptivity is always *downward* from a baseline data rate and can therefore be considered in effect *asymmetrical* also. Not until power is recycled and the ATU-C retrains itself will the data rate increase back to its original base level. This fact he attributed as being the typical cause for customer service calls dealing with service “slowing down” complaints. Also noteworthy were his comments regarding Frontier’s choice not to market an additional “RADSL” product, as I discussed in the section “The “Rate Adaptive” Controversy” (pp. 47 and 48). Frontier’s decision to limit data rates at the DSLAM port (by limiting carrier frequency), rather than at the CPE, precludes offering a variable bit rate service in exchange for the benefits of lower network costs and increased flexibility in network maintenance and monitoring.
**End Notes**


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Web Sites

Miscellaneous


Appendix A

**EC**: reuses higher quality, lower frequency spectrum for increased reach and throughput. Optional in G.DMT.

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**FDM**: loses more of its useable downstream bandwidth on long loops than EC. Figure 4 in G.DMT and G.Lite.

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**EC vs. FDM DMT ADSL Frequency Spectra**

(Source: Communications Systems Design, June 1999, “The G.DMT and G.Lite Recommendations, Part 2”, Figure #4)

http://www.commsdesign.com/main/1999/06/
Appendix B

QAM-16 Constellation
(Source: Eicon Networks Corp., On-line training course “ADSL: Theory and Practice”.)
http://www.eicon.com/support/training/default.htm