ADSL and DMT

OUTLINE

- Overview of xDSL
- ADSL System architecture
- Framing
- Scrambling & FEC
- Interleaving
- Tone ordering
- Constellation encoding
- Wei’s Trellis coding
- Modulation
- Other Issues

Overview of xDSL

- Different techniques for high speed transmission over copper
- The ADSL rates and Configurations
- DMT vs. CAP Modulation
- Overview of DMT for ADSL
High Speed Data Over Copper Wires

- ADSL is one of several Digital Subscriber Line (xDSL) modem technologies
  - High-bit-rate DSL (HDSL)
  - Symmetric DSL (SDSL)
  - Rate Adaptive DSL (RADSL)
  - Very-high-data-rate DSL (VDSL)
- These modem technologies offer trade-offs between distance and bandwidth
- ADSL supports much higher speed in the down-link (Central office-to-Remote) than in the up-link (Remote-to-Central office)

![Digital Network Splitter](PSTN-Splitter-Copper-wire-Digital-Services-Splitter-POTS)

Central Office

Remote (subscriber)

Different Techniques [1]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Data rate</th>
<th>Mode</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>V.xx</td>
<td>Voice band modems</td>
<td>1.2 - 56 kbps</td>
<td>Duplex</td>
<td>Data</td>
</tr>
<tr>
<td>DSL</td>
<td>Digital subscriber line</td>
<td>160 kbps</td>
<td>Duplex</td>
<td>ISDN, voice + data</td>
</tr>
<tr>
<td>HDSL</td>
<td>High data rate digital subscriber line</td>
<td>1.544 Mbps 2.048 Mbps</td>
<td>Duplex</td>
<td>T1/E1 services. WAN/LAN</td>
</tr>
<tr>
<td>SDSL</td>
<td>Single line digital subscriber line</td>
<td>1.544 Mbps 2.048 Mbps</td>
<td>Duplex</td>
<td>HDLS services + Premises access</td>
</tr>
<tr>
<td>ADSL</td>
<td>Asymmetric digital subscriber line</td>
<td>1.5 - 9 Mbps 16-640 kbps</td>
<td>Down UP</td>
<td>Internet, video on demand, LAN's, interactive MM</td>
</tr>
<tr>
<td>VDSL</td>
<td>Very high rate digital subscriber line</td>
<td>13 - 52 Mbps 1.5 - 2.3 Mbps</td>
<td>Down UP</td>
<td>ADSL services + HDTV</td>
</tr>
</tbody>
</table>
Distance Attenuation

- Copper wires introduce substantial attenuation
- The attenuation increases with frequency
- For a given data rate, the maximum length of copper wire is limited as shown in the figure
- The length of subscriber wires varies considerably. In North America, 80% of home/business phones are connected by wires shorter than 5.5 km.

ADSL Rates

- Downstream data rates depend on several factors; such as: length and gauge of the copper wire, presence of bridge taps and cross-coupled interference
- ADSL modems provide data rates consistent with North American (and European) digital Hierarchies

<table>
<thead>
<tr>
<th>Data (Mbps)</th>
<th>Wire size (mm)</th>
<th>Distance (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 / 2.0</td>
<td>0.5</td>
<td>18,000</td>
</tr>
<tr>
<td>1.5 / 2.0</td>
<td>0.4</td>
<td>15,000</td>
</tr>
<tr>
<td>6.1</td>
<td>0.5</td>
<td>12,000</td>
</tr>
<tr>
<td>6.1</td>
<td>0.4</td>
<td>9,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Downstream Bearer Channels</th>
<th>Duplex Bearer Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>n x 1.536 Mbps</td>
<td>C Channel</td>
</tr>
<tr>
<td>1.536 Mbps</td>
<td>16 kbps</td>
</tr>
<tr>
<td>3.072 Mbps</td>
<td>64 kbps</td>
</tr>
<tr>
<td>4.608 Mbps</td>
<td></td>
</tr>
<tr>
<td>6.144 Mbps</td>
<td></td>
</tr>
<tr>
<td>n x 2.048 Mbps</td>
<td>Optional Channel</td>
</tr>
<tr>
<td>2.048 Mbps</td>
<td>160 kbps</td>
</tr>
<tr>
<td>4.096 Mbps</td>
<td>384 kbps</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>n x 2.048 Mbps</td>
</tr>
<tr>
<td></td>
<td>2.048 Mbps</td>
</tr>
<tr>
<td></td>
<td>4.096 Mbps</td>
</tr>
</tbody>
</table>
There are two ADSL modes: Frequency Division Multiplexing (FDM) and Echo Cancellation (EC).

In the FDM mode, three separate bands are allocated to POTS, Upstream and Downstream.

In the EC mode, the up-stream signal overlaps the lower spectrum of the down-stream signals. The overlap is resolved by Echo Cancellation.

- **FDM**
  - POTS
  - Up-stream
  - Down-stream (Central Office to Remote)

- **EC**
  - POTS
  - Up-stream
  - Down-stream

**DMT vs. CAP**

- **CAP** Carrierless Amplitude & Phase Modulation
- **DMT** Discrete Multi-Tone Modulation

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Why DMT is better than CAP?

- **Rate Adaptation**
  - Breaking up the available bandwidth into many parallel channels provides a flexible means for adapting the data rate to user’s requirements

- **Adaptation to the channel Conditions**
  - The number of bits allocated to each channel are adjusted for individual channels
  - The QAM constellations are adapted to the channel conditions.

Overview of DMT

- \( N \) = number of tones = 255
- \( D_f \) = frequency spacing between tones = 4.3125 kHz
- Tone # 64 (276 kHz) serves as a pilot
- Tone position # 256 is the Nyquist frequency and shall not be used for data
Overview of DMT (cont.)

- The lower value of "n" is determined by the ADSL mode: Echo Cancellation (EC) or Frequency Division Multiplexing (FDM)
- In the EC mode, the lowest n is determined by the POT/ADSL split filter.
- In the FDM mode, the lowest n is determined by the up-stream/down-stream filter split

![Diagram showing Down-stream in EC and FDM modes](image)

The Modulation Process

- Each tone is modulated by a complex number (data)

$$ Z_k = x_k + j y_k $$

- All 255 modulated carriers are added to form the final signal
- We can achieve the same results digitally using the Inverse Discrete Fourier Transform

$$ s_k(t) = \text{Re}\{z_k \cdot \exp[2\pi f_k t]\} $$
**The Inverse Discrete Fourier Transform (IDFT)**

- The IDFT generates "time samples" from "frequency samples"
- Since we require "real" time samples, we must feed to the IDFT the frequency samples and their complex conjugate mirrored values.

\[
\{ Z_k; k=1, \ldots, 225 \}
\]

- Hermitian Symmetry

\[
\{ Z_k'; k=1, \ldots, 512 \}
\]

\[
\{ Z_k'=\text{conj}(Z_{512-k}'); k=257 \text{ to } 512 \}
\]

- Parallel to Serial

DAC

**ADSL System Architecture**

- There are two standard types of channels in ADSL:
  - **Simplex** Denoted by \( AS_x \) where \( x = 0, 1, 2 \) and 3
    - \( AS0 \) \( n_0 \times 1.536 \text{ Mb/s} \) \( n_0 = 0, 1, 2, 3 \) or 4
    - \( AS1 \) \( n_1 \times 1.536 \text{ Mb/s} \) \( n_1 = 0, 1, 2 \) or 3
    - \( AS2 \) \( n_2 \times 1.536 \text{ Mb/s} \) \( n_2 = 0, 1 \) or 2
    - \( AS3 \) \( n_3 \times 1.536 \text{ Mb/s} \) \( n_3 = 0 \) or 1
  - **Duplex** Denoted by \( LS_x \) where \( x = 0, 1 \) and 2
    - \( LS0 \) Also known as "C" \( 16 \) or 64 kb/s
    - \( LS1 \) \( 160 \text{ kb/s} \)
    - \( LS2 \) \( 384 \) or 576 kb/s

- There are other optional and vendor-specific channels
The maximum rates by transport classes are as follows:

<table>
<thead>
<tr>
<th>Transport Class</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Down-stream simplex</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Capacity</td>
<td>6.144 Mb/s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Channel options</td>
<td>1.536 Mb/s</td>
<td>4.608 Mb/s</td>
<td>3.072 Mb/s</td>
<td>1.536 Mb/s</td>
</tr>
<tr>
<td></td>
<td>3.072 Mb/s</td>
<td>3.072 Mb/s</td>
<td>3.072 Mb/s</td>
<td>3.072 Mb/s</td>
</tr>
<tr>
<td></td>
<td>4.608 Mb/s</td>
<td>4.608 Mb/s</td>
<td>4.608 Mb/s</td>
<td>4.608 Mb/s</td>
</tr>
<tr>
<td></td>
<td>6.144 Mb/s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Duplex</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Capacity</td>
<td>640 kb/s</td>
<td>4.608 Mb/s</td>
<td>3.072 Mb/s</td>
<td>1.536 Mb/s</td>
</tr>
<tr>
<td>Channel options</td>
<td>576 kb/s</td>
<td>384 kb/s</td>
<td>384 kb/s</td>
<td>384 kb/s</td>
</tr>
<tr>
<td></td>
<td>384 kb/s</td>
<td>384 kb/s</td>
<td>160 kb/s</td>
<td>160 kb/s</td>
</tr>
<tr>
<td></td>
<td>160 kb/s</td>
<td>160 kb/s</td>
<td>64 kb/s</td>
<td>64 kb/s</td>
</tr>
<tr>
<td></td>
<td>64 kb/s</td>
<td>64 kb/s</td>
<td>64 kb/s</td>
<td>64 kb/s</td>
</tr>
</tbody>
</table>

The "C" channel

- 16 kb/s
- 64 kb/s

ADSL System Architecture (cont.)
**The Central Office Transmitter**

- The block diagram illustrates the basic processing blocks of the central office transmitter (ATU-C) and the order of processing.
- The block diagram of the remote unit (ATU-R) is identical with the transmitted signals limited to LS₀, LS₁, and LS₂.

```
       MUX/Synch Control
         |                |
         |                | CRC(i)
         |                | scrambler & FEC
A       |                | Tone Ordering
         |                | interleave
         |                | Constellation encoder & gain scaler
         |                | IDF
         |                | Output P/S buffer
         |                | 511
         |                | 0
         |                | DAC

```

**Initialization**

- During the initialization phase, test signals are exchanged between the remote and central stations.
- The remote station determines the quality of each segment (tone) of the downstream spectrum (central to remote).
- The remote station determines how many bits should be allocated to each tone. It also determines the scaling gain of each tone.
- Tones are listed in an ascending order of their bit allocations, and the table of ordered tones (bits and gains) are sent back to the central station.
Bits and Gains Allocations

- During initialization, the down-stream channel is tested by a broadband pseudo random signal called C-MEDLY.
- The ATU-R receiver calculates the maximum number of bits per symbol that each down-stream channel can support.

![Diagram showing transmitted and received signals over frequency range 1.1 MHz.]

- The target error rate is $10^{-7}$ and the performance margin is 6 dB.

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Bits and Gains Allocations

- A table is sent back to the ATU-C receiver with bit allocation, $b_k$, and gain adjustment factor, $g_k$. \( \{ b_k, g_k ; k=1, 255 \} \)
- When both $b_k$ and $g_k$ are zero, carrier # $k$ is not used permanently.
- When $b$ is zero and $g$ is unity, carrier # $k$ is not used temporarily.
- Gross gain adjustment of 6 dB may be required for carriers above carrier #51.
- Fine gain adjustment of 1.5 dB may be required to equalize the expected error rate performance across the tones.

![Diagram showing high attenuation region at 225 kHz frequency range.]

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ATU-C Super Frame

- The down-stream data is transmitted in 17 msec super frames. Each super frame consists of:
  - \( \{ 68 \text{ data frames} + \text{one synchronization frame} \} \)
- Each of the data frames has two sections:
  - **Fast Data & Interleaved Data**
- The interleaved data is more protected but exhibits larger delay.

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ATU-C Super Frame (cont.)

- Fast Data & Interleaved Data
  - The interleaved data is more protected but exhibits larger delay.
Frame Structure

- Each data stream (AS0, AS1, AS2, AS3, LS0, LS1, and LS2) is assigned to either the fast or the interleaved buffers.
- A pair of bytes \([B_f, B_i]\) are transmitted for each data stream, where \(B_f\) and \(B_i\) designate the number of bytes allocated to the fast and interleaved buffers.

The Fast Buffer

<table>
<thead>
<tr>
<th>fast byte</th>
<th>(B_f) (AS0)</th>
<th>(B_f) (AS1)</th>
<th>(B_f) (AS2)</th>
<th>(B_f) (AS3)</th>
<th>(C_f) (LS0)</th>
<th>(B_i) (LS1)</th>
<th>(B_i) (LS2)</th>
<th>AEX</th>
<th>LEX</th>
<th>FEC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K_f) bytes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(R_{fast}) bytes</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(N_f) bytes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(AEX = 0\) if the simplex streams (ASx) have no data
\(LEX = 0\) if both the simplex (ASx) and duplex (LSx) streams have no data

The Interleaved Buffer

\(S \times N_m\) bytes

Data Frame \#: 0 Data Frame \#: 1 Data Frame \#: 2 Data Frame \#: (S-1) FEC

<table>
<thead>
<tr>
<th>synch byte</th>
<th>(B_f) (AS0)</th>
<th>(B_f) (AS1)</th>
<th>(B_f) (AS2)</th>
<th>(B_f) (AS3)</th>
<th>(C_f) (LS0)</th>
<th>(B_i) (LS1)</th>
<th>(B_i) (LS2)</th>
<th>AEX</th>
<th>LEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_m) bytes</td>
<td>(N_m) bytes</td>
<td>(N_m) bytes</td>
<td>(N_m) bytes</td>
<td>(R_{inter}) bytes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(N_m\) bytes (data frame @ ref. point A)

\(AEX = 0\) if the simplex streams (ASx) have no data
\(LEX = 0\) if both the simplex (ASx) and duplex (LSx) streams have no data
Cyclic Redundancy Check (CRC)

<table>
<thead>
<tr>
<th>Super Frame # n</th>
<th>Super Frame # (n+1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRC bytes for super frame # n</td>
<td></td>
</tr>
<tr>
<td>Two 8-bit CRC-bytes in the fast byte</td>
<td></td>
</tr>
</tbody>
</table>

Generator Polynomial = $D^8 \oplus D^5 \oplus D^3 \oplus D^2 \oplus 1$

Switches in position "1" during the K clock cycles of the message
Switches in position "2" during the following 8 CRC clock cycles

Data Scrambling

\[ \text{out}(n) = \text{data}(n) \oplus \text{out}(n - 18) \oplus \text{out}(n - 23) \]

- The scrambling is performed on the binary data streams in the fast and interleaved buffers.
- The fast and interleaved data are scrambled separately
Reed-Solomon FEC Encoder

- Galois Field \( G(256) \). The symbol length is \( m = 8 \) bits
- \( K \) data bytes produces \( N \) coded bytes
- \( K \) and \( N \) depend on the transport class and on the type of buffer (fast or interleaved)
- For the fast buffered data the default value for \( R_{dsf} = N - K \) is 4
- For interleaved data, \( "S" \) MUX frames (i.e. \( S \) DTM symbols) are combined to form the \( K \) data bytes. The number of redundancy bits \( R_{dsi} \), the number of frames and interleaving depth are given in tables.

R-S Code Words Interleaving

Interleaving Example
Block size = 5
Delay parameter = \( D = 2 \)
\( D(m) = (D-1) \times m \)
**Tones Ordering**

- Test signal during initialization
- Ascending order in terms of the # of bits
- \( b_k \), bit allocation
- \( f_k \)

<table>
<thead>
<tr>
<th>Bit Allocation Table</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b_0 )</td>
</tr>
<tr>
<td>( b_1 )</td>
</tr>
<tr>
<td>( b_{255} )</td>
</tr>
</tbody>
</table>

**Constellation Encoder (without Trellis Coding)**

- The duration of a data frame is **246.377 \( \mu \text{sec} \)** (68/69 x 250 \( \mu \text{sec} \)).
- The data in the fast and interleaved buffers at reference point C form one DMT symbol. The data at this point is called the **DMT Symbol Buffer**.
- Mapping the FEC-coded data onto the DMT symbol occurs according to the following steps:
  1. Bit extraction
  2. Constellation encoder
  3. Gain scaling
  4. Multi-tone modulation

[Diagram of Constellation Encoder (without Trellis Coding)]
### Bit Extraction

The DMT symbol buffer, M bits

<table>
<thead>
<tr>
<th>LSB</th>
<th>MSB</th>
</tr>
</thead>
</table>

re-ordered tones

- $b_0'$
- $b_1'$
- $b_2'$
- $b_k'$
- $b_{255}'$

| Value | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
|-------|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Index | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |

- $2 \leq b_k' \leq 15$

$v_k = \{v_{b_k'-1}, v_{b_k'-2}, \ldots, v_1, v_0\}$

- largest number of bits

### Expanding Constellations

Continue by replacing each element "n" by a 2x2 block with the following indices:

- $b=2$
- $b=3$
- $b=4$
- $b=5$

4n+1 4n+2 4n 4n+3
• Trellis coding can optionally be used to improve the performance.
• The coding is done according to Wei’s four-dimensional trellis coding
• Bits are extracted for pairs of tones. The number of extracted bits are one less than the number stated in the reordered table.
• An extra step [Bit Conversion] is required

**Constellation Encoder (with Trellis Coding)**

Buffered Data

$$\{u_k; k=1,..., 225\}$$

Bit extraction

$$\{v_k; k=1,..., 225\}$$

Bit conversion

$$\{w_k; k=1,..., 225\}$$

Constellation encoder

$$\{Z_k; k=1,..., 225\}$$

Gain scaling

$$\{Z'_k = g_kZ_k; k=1,..., 225\}$$

To modulator

**Constellation Encoder**

Bit allocation Table

$$\begin{array}{cccc}
  b_0' & b_1' & x & y & b_{255}' \\
\end{array}$$

Extract z bits

$$z = (x+y-1)$$

Wei’s encoder

$$\{v_k; k=1,..., 225\}$$

x-bit constellation

$$\{w_k; k=1,..., 225\}$$

y-bit constellation

$$Z_i$$

$$Z_{i+1}$$
Bit Conversion

\[ u_2 \rightarrow w_{y-1} \]
\[ u_{2-1} \rightarrow w_{y-2} \]
\[ u_{2-y+3} \rightarrow w_2 \]
\[ u_{2-y+2} \rightarrow v_{z-y} \]
\[ u_{2-y+1} \rightarrow v_{z-y-1} \]

\[ u_4 \rightarrow v_2 \]
\[ u_3 \rightarrow v_1 \]
\[ u_2 \rightarrow v_0 \]
\[ u_1 \rightarrow w_1 \]
\[ u_0 \rightarrow w_0 \]

Encoding and Mapping

\[ u_3 \rightarrow v_0 \]
\[ u_2 \rightarrow v_1 \]
\[ u_1 \rightarrow w_0 \]
\[ u_0 \rightarrow w_1 \]
**IDFT Modulation**

256 Complex Numbers

\[ \{ Z_k; k=1, \ldots, 225 \} \]

\[ \{ Z_k' = \text{conj}(Z_{512-k}); k=257 \text{ to } 512 \} \]

\[ \{ Z_k'; k=1, \ldots, 512 \} \]

Hermitian Symmetry

\[ \{ Z_k' = g_k Z_k; k=1, \ldots, 225 \} \]

Gains Scaling Factors

\{ \{ g_k; k=1, \ldots, 225 \} \}

From Tone Re-ordering Table

IDFT

\[ x_k = \sum_{m=0}^{255} \left( \frac{2\pi km}{256} \right) Z_m; k=0 \text{ to } 511 \]

Parallel to Serial

DAC

**Other Issues**

- Several ADSL trials are currently underway and the reported results are encouraging.
- ADSL will speed up the transmission on the "last mile", the rest of the internet is not ready for 6 Mb/s speed.
- ADSL is fully capable of handling ATM traffic. ATM traffic rates are included in the current standards, and ATM / ADSL framing standard is ready.
- "Dial Up" ADSL equipment are commercially available.
- ADSL is the cheapest way to connect high speed data over copper.