Introduction to ADSL Modems

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http://www.ece.utexas.edu/~bevans/projects/adsl
Outline

• **Broadband Access**
  – Applications
  – Digital Subscriber Line (DSL) Standards

• **ADSL Modulation Methods**
  – ADSL Transceiver Block Diagram
  – Quadrature Amplitude Modulation
  – Multicarrier Modulation

• **ADSL Transceiver Design**
  – Inter-symbol Interference
  – Time-Domain Equalization
  – Frequency-Domain Equalization

• **Conclusion**
# Applications of Broadband Access

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<th>Residential Application</th>
<th>Downstream rate (kb/s)</th>
<th>Upstream rate (kb/s)</th>
<th>Willing to pay</th>
<th>Demand Potential</th>
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<tbody>
<tr>
<td>Database Access</td>
<td>384</td>
<td>9</td>
<td>High</td>
<td>Medium</td>
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<tr>
<td>On-line directory; yellow pages</td>
<td>384</td>
<td>9</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Video Phone</td>
<td>1,500</td>
<td>1,500</td>
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<td>Medium</td>
</tr>
<tr>
<td>Home Shopping</td>
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<td>Low</td>
<td>Medium</td>
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<tr>
<td>Video Games</td>
<td>1,500</td>
<td>1,500</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Internet</td>
<td>3,000</td>
<td>384</td>
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</tr>
<tr>
<td>Broadcast Video</td>
<td>6,000</td>
<td>0</td>
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<td>High definition TV</td>
<td>24,000</td>
<td>0</td>
<td>High</td>
<td>Medium</td>
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<table>
<thead>
<tr>
<th>Business Application</th>
<th>Downstream rate (kb/s)</th>
<th>Upstream rate (kb/s)</th>
<th>Willing to pay</th>
<th>Demand Potential</th>
</tr>
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<tbody>
<tr>
<td>On-line directory; yellow pages</td>
<td>384</td>
<td>9</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Financial news</td>
<td>1,500</td>
<td>9</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Video phone</td>
<td>1,500</td>
<td>1,500</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Internet</td>
<td>3,000</td>
<td>384</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Video conference</td>
<td>3,000</td>
<td>3,000</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Remote office</td>
<td>6,000</td>
<td>1,500</td>
<td>High</td>
<td>Medium</td>
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<tr>
<td>LAN interconnection</td>
<td>10,000</td>
<td>10,000</td>
<td>Medium</td>
<td>Medium</td>
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<tr>
<td>Supercomputing, CAD</td>
<td>45,000</td>
<td>45,000</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>
DSL Broadband Access

DSLAM

ADSL modem

Central Office

Voice Switch

LPF

PSTN

Internet

downstream

Customer Premises

ADSL modem

LPF

upstream
## DSL Broadband Access Standards

<table>
<thead>
<tr>
<th>xDSL</th>
<th>Meaning</th>
<th>Data Rate</th>
<th>Mode</th>
<th>Applications</th>
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<tbody>
<tr>
<td><strong>ISDN</strong></td>
<td>Integrated Services Digital Network</td>
<td>144 kbps</td>
<td>Symmetric</td>
<td>Internet Access, Voice, Pair Gain (2 channels)</td>
</tr>
<tr>
<td><strong>T1</strong></td>
<td>T-Carrier One (requires two pairs)</td>
<td>1.544 Mbps</td>
<td>Symmetric</td>
<td>Business, Internet Service</td>
</tr>
<tr>
<td><strong>HDSL</strong></td>
<td>High-Speed Digital Subscriber Line (requires two pairs)</td>
<td>1.544 Mbps</td>
<td>Symmetric</td>
<td>Pair Gain (12 channels), Internet Access, T1/E1 replacement</td>
</tr>
<tr>
<td><strong>SHDSL</strong></td>
<td>Single Line HDSL</td>
<td>1.544 Mbps</td>
<td>Symmetric</td>
<td>Same as HDSL except pair gain is 24 channels</td>
</tr>
<tr>
<td><strong>Splitterless ADSL</strong></td>
<td>Splitterless Asymmetric DSL (G.Lite)</td>
<td>Up to 1.5 Mbps</td>
<td>Downstream</td>
<td>Internet Access, Video Phone</td>
</tr>
<tr>
<td><strong>Full-Rate ADSL</strong></td>
<td>Asymmetric DSL (G.DMT)</td>
<td>Up to 10 Mbps</td>
<td>Downstream</td>
<td>Internet Access, Video Conferencing, Remote LAN Access</td>
</tr>
<tr>
<td><strong>VDSL</strong></td>
<td>Very High-Speed Digital Subscriber Line (proposed)</td>
<td>Up to 22 Mbps</td>
<td>Downstream</td>
<td>Internet Access, Video-on-demand, ATM, Fiber to the Hood</td>
</tr>
</tbody>
</table>

**Meanings:**
- ISDN: Integrated Services Digital Network
- T1: T-Carrier One (requires two pairs)
- HDSL: High-Speed Digital Subscriber Line (requires two pairs)
- SHDSL: Single Line HDSL
- Splitterless ADSL: Splitterless Asymmetric DSL (G.Lite)
- Full-Rate ADSL: Asymmetric DSL (G.DMT)
- VDSL: Very High-Speed Digital Subscriber Line (proposed)

**Applications:**
- Internet Access, Voice, Pair Gain (2 channels)
- Internet Access, T1/E1 replacement
- Internet Access, T1/E1 replacement
- Internet Access, Video Phone
- Internet Access, Video Conferencing, Remote LAN Access
- Internet Access, Video-on-demand, ATM, Fiber to the Hood

Courtesy of Shawn McCaslin (Cicada Semiconductor, Austin, TX)
Spectral Compatibility of xDSL

- POTS
- ISDN
- ADSL - USA
- ADSL - Europe
- HDSL/SHDSL
- HomePNA
- Optional
- VDSL - FDD

Frequency (Hz):
- 10k
- 100k
- 1M
- 10M
- 100M

- Upstream
- Downstream
- Mixed

1.1 MHz
12 MHz
ADSL Modem

TRANSMITTER

- S/P
- Quadrature amplitude modulation (QAM) encoder
- Mirror data and N-IFFT
- Add cyclic prefix
- P/S
- D/A + transmit filter

RECEIVER

- N/2 subchannels
- N real samples

- P/S
- QAM demod decoder
- Invert channel = frequency domain equalizer
- N-FFT and remove mirrored data
- Remove cyclic prefix
- S/P
- Time domain equalizer (FIR filter)
- Receive filter + A/D

N/2 subchannels
N real samples
Bit Manipulations

- **Serial-to-parallel converter**
  - Example of one input bit stream and two output words

- **Parallel-to-serial converter**
  - Example of two input words and one output bit stream

![Diagram showing S/P converter with input and output examples](image)
Amplitude Modulation by Cosine Function

• Multiplication in time is convolution in Fourier domain

\[ y(t) = f(t) \cos(\omega_0 t) \]
\[ Y(\omega) = \frac{1}{2\pi} F(\omega) \ast \pi(\delta(\omega + \omega_0) + \delta(\omega - \omega_0)) \]

• Sifting property of the Dirac delta functional

\[ x(t) \ast \delta(t) = \int_{-\infty}^{\infty} \delta(\tau)x(t-\tau)d\tau = x(t) \]
\[ x(t) \ast \delta(t-t_0) = \int_{-\infty}^{\infty} \delta(\tau-t_0)x(t-\tau)d\tau = x(t-t_0) \]

• Fourier transform property for modulation by a cosine

\[ Y(\omega) = \frac{1}{2} F(\omega + \omega_0) + \frac{1}{2} F(\omega - \omega_0) \]
Amplitude Modulation by Cosine Function

- **Example:** \( y(t) = f(t) \cos(\omega_0 t) \)
  - \( f(t) \) is an ideal lowpass signal
  - Assume \( \omega_1 \ll \omega_0 \)
  - \( Y(\omega) \) is real-valued if \( F(\omega) \) is real-valued

\[
Y(\omega) = \frac{1}{2} F(\omega + \omega_0) + \frac{1}{2} F(\omega - \omega_0)
\]

- Demodulation is modulation then lowpass filtering
- Similar derivation for modulation with \( \sin(\omega_0 t) \)
Amplitude Modulation by Sine Function

- **Multiplication in time is convolution in Fourier domain**

\[
y(t) = f(t) \sin(\omega_0 t)
\]

\[
Y(\omega) = \frac{1}{2\pi} F(\omega) \ast j\pi (\delta(\omega + \omega_0) - \delta(\omega - \omega_0))
\]

- **Sifting property of the Dirac delta functional**

\[
x(t) \ast \delta(t) = \int_{-\infty}^{\infty} \delta(\tau) x(t - \tau) d\tau = x(t)
\]

\[
x(t) \ast \delta(t - t_0) = \int_{-\infty}^{\infty} \delta(t - t_0) x(t - \tau) d\tau = x(t - t_0)
\]

- **Fourier transform property for modulation by a sine**

\[
Y(\omega) = \frac{j}{2} F(\omega + \omega_0) - \frac{j}{2} F(\omega - \omega_0)
\]
Amplitude Modulation by Sine Function

- **Example:** \( y(t) = f(t) \sin(\omega_0 t) \)
  - \( f(t) \) is an ideal lowpass signal
  - Assume \( \omega_1 \ll \omega_0 \)
  - \( Y(\omega) \) is imaginary-valued if \( F(\omega) \) is real-valued

\[
Y(\omega) = \frac{j}{2} F(\omega + \omega_0) - \frac{j}{2} F(\omega - \omega_0)
\]

- **Demodulation is modulation then lowpass filtering**
Quadrature Amplitude Modulation (QAM)

- One carrier
- Single signal, occupying the whole available bandwidth
- The symbol rate is the bandwidth of the signal being centered on carrier frequency

**Diagram:**
- **Constellation encoder**
- **Modulator**
  - **Lowpass filter**
- **Bandpass**
  - $\cos(2\pi f_c t)$
  - $\sin(2\pi f_c t)$

**Mathematical expressions:**
- $Q = X_i$
- $I = 00110$
- $\cos(2\pi f_c t)$
- $\sin(2\pi f_c t)$

**Diagram elements:**
- **Bits**
- **I**
- **Q**
- **TX**
- **Lowpass filter**
- **Bandpass**
- **Channel**
- **Magnitude**
- **Frequency**
- $f_c$
Multicarrier Modulation

- Divide broadband channel into narrowband subchannels
- Discrete Multitone (DMT) modulation
  - Based on fast Fourier transform (related to Fourier series)
  - Standardized for ADSL
  - Proposed for VDSL

Subchannels are 4.3 kHz wide in ADSL
Multicarrier Modulation by Inverse FFT

\[ g(t) : \text{pulse shaping filter} \]

\[ X_i : \text{ith symbol from encoder} \]
Multicarrier Modulation in ADSL

\[ X_i = X_0, X_1, X_2, \ldots, X_{N-1} \]

N time samples

\[ X_{1}^*, X_{2}^*, X_{N/2-1}^*, X_{N/2}^* \]

N/2 subchannels (carriers)

QAM

[Diagram of QAM modulation and inverse fast Fourier transform (IFFT)]
Multicarrier Modulation in ADSL

In the diagram:
- Inverse FFT
- Samples
- Symbol \( (i) \)
- Copy
- Symbol \( (i+1) \)
- D/A + transmit filter

Table: ADSL

<table>
<thead>
<tr>
<th></th>
<th>Downstream</th>
<th>Upstream</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP</td>
<td>32</td>
<td>4</td>
</tr>
<tr>
<td>N</td>
<td>512</td>
<td>64</td>
</tr>
</tbody>
</table>

CP: Cyclic Prefix
Multicarrier Demodulation in ADSL

- N-point Fast Fourier Transform (FFT)
- N/2 subchannels (carriers)
- N time samples

\[ \tilde{X}_0 \quad \tilde{X}_{N/2-1} \quad \tilde{X}_{N/2} \quad \tilde{X}^*_{N/2-1} \quad \tilde{X}^*_1 \]

\[ \tilde{x}_0 \quad \tilde{x}_1 \quad \tilde{x}_2 \quad \cdots \quad \tilde{x}_{N-1} \]
Inter-symbol Interference (ISI)

- **Ideal channel**
  - Impulse response is an impulse
  - Frequency response is flat

- **Non-ideal channel causes ISI**
  - Channel memory
  - Magnitude and phase variation

- **Received symbol is weighted sum of neighboring symbols**
  - Weights are determined by channel impulse response
Channel Impulse Response

Impulse response of the Channel - 12 kft 26AWG

- Amplitude vs. time samples @ 2.2 MHz
- Magnitude (dBm) vs. frequency (Hz)
Channel Impulse Response

Impulse response of the Channel - ANSI9

[Graph showing channel impulse response with amplitude on the y-axis and time samples at 2.2 MHz on the x-axis.]

[Graph showing magnitude in dBm vs frequency.]
Cyclic Prefix Helps in Fighting ISI

• **Provide guard time between successive symbols**
  – No ISI if channel length is shorter than $\nu + 1$ samples

• **Choose guard time samples to be a copy of the beginning of the symbol – cyclic prefix**
  – Cyclic prefix converts linear convolution into circular convolution
  – Need circular convolution so that
    \[ \text{symbol} \otimes \text{channel} \iff \text{FFT(symbol)} \times \text{FFT(channel)} \]
  – Then division by the FFT(channel) can undo channel distortion

\[ \nu \text{ samples} \quad N \text{ samples} \]
Cyclic Prefix Helps in Fighting ISI

Repeated symbol * equal to be removed cyclic prefix

desired symbol equal received symbol + cp
Combat ISI with Time-Domain Equalizer

- Channel length is usually longer than cyclic prefix
- Use finite impulse response (FIR) filter called a time-domain equalizer to shorten channel impulse response to be no longer than cyclic prefix length
Convolutions Review

- **Discrete-time convolution**
  
  \[ y[k] = \sum_{m=-\infty}^{\infty} h[m] x[k-m] \]

- **For every** \( k \), we compute a new summation

- **Continuous-time convolution**
  
  \[ y(t) = \int_{-\infty}^{\infty} h(\tau) x(t-\tau) \, d\tau \]

- **For every value of** \( t \), we compute a new integral

\[ x[k] \rightarrow h[k] \rightarrow y[k] \]

Represented by its impulse response

\[ x(t) \rightarrow h(t) \rightarrow y(t) \]

Represented by its impulse response
Finite Impulse Response (FIR) Filter

- Assuming that $h[k]$ is causal and has finite duration from $k = 0, \ldots, N-1$

$$y[k] = \sum_{m=0}^{N-1} h[m] x[k-m]$$

- Block diagram of an implementation (called a finite impulse response filter)
Example Time-Domain Equalizer

- Minimize mean squared error
  \[ E\{e_k^2\} \text{ where } e_k = b_{k-\Delta} - h_k w_k \]
  - Chose length of \( b_k \) to shorten length of \( h_k w_k \)

- Disadvantages
  - Does not consider channel capacity
  - Deep notches in equalizer frequency response
Frequency Domain Equalizer in ADSL

- **Problem:** FFT coefficients (constellation points) have been distorted by the channel.

- **Solution:** Use Frequency-domain Equalizer (FEQ) to invert the channel.

- **Implementation:** N/2 single-tap filters with complex coefficients.
Frequency Domain Equalizer in ADSL

\[ Y_i = c_i \tilde{X}_i \]

\[ \tilde{X}_0, \tilde{X}_1, \ldots, \tilde{X}_{N/2-1} \]

\[ Y_0, Y_1, Y_{N/2-1} \]

QAM decoder

\[ 0101 \]

\[ \text{Q} \]

\[ \text{I} \]
ADSL Modem

TRANSMITTER

- S/P
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- Invert channel = frequency domain equalizer
- \(N\)-FFT and remove mirrored data
- Remove cyclic prefix
- S/P
- Remove cyclic prefix
- Time domain equalizer (FIR filter)
- Receive filter + A/D
Crosstalk and Near-End Echo

- TX
- RX
- H
cable
- NEXT
- Near-End echo
- FEXT
**ADSL vs. FEXT, NEXT, Near-end Echo**

- **ADSL with Freq. Division Multiplexing - FDM**
  - Near-End Echo filtered out
  - Self-NEXT (NEXT from another ADSL) mostly filtered out
  - FEXT and NEXT (from another type of DSL) are problems

- **ADSL with overlapped spectrum (Echo Cancelled)**
  - Near-End Echo Eliminated using an echo canceller
  - FEXT, NEXT and self-NEXT are a problem
  - Larger Spectrum available for downstream – higher data rate