Introduction to ADSL Modems

Original Lecture Notes developed by

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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

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### Applications of Broadband Access

<table>
<thead>
<tr>
<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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</thead>
<tbody>
<tr>
<td>Database Access</td>
<td>384</td>
<td>9</td>
<td>High</td>
<td>Medium</td>
</tr>
<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>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Home Shopping</td>
<td>1,500</td>
<td>64</td>
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<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>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Broadcast Video</td>
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<td>384</td>
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<td>High</td>
</tr>
<tr>
<td>High definition TV</td>
<td>24,000</td>
<td>0</td>
<td>High</td>
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<table>
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<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>
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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>
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<td>Medium</td>
<td>Low</td>
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<td>Video phone</td>
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<tr>
<td>Internet</td>
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<td>384</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Video conference</td>
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<td>3,000</td>
<td>High</td>
<td>Low</td>
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<tr>
<td>Remote office</td>
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<td>Medium</td>
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<tr>
<td>LAN interconnection</td>
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<td>Medium</td>
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<tr>
<td>Supercomputing, CAD</td>
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<td>45,000</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>
DSL Broadband Access

DSLAM - Digital Subscriber Line Access Multiplexer

LPF – Lowpass Filter (passes voiceband frequencies)
Spectral Compatibility of xDSL

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ADSL Modem

**TRANSMITTER**

Bits

00110

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 → channel

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Bit Manipulations

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

- Parallel-to-serial converter

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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

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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

Every subchannel behaves like QAM
Multicarrier Modulation by Inverse FFT

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Multicarrier Modulation in ADSL

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Multicarrier Modulation in ADSL

- **Inverse FFT**
- **N samples**
- **v samples**

### ADSL Table

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

**CP**: Cyclic Prefix

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Multicarrier Demodulation in ADSL

- \( N \)-point Fast Fourier Transform (FFT)
- \( N/2 \) subchannels (carriers)
- S/P

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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

Threshold at zero

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Channel Impulse Response

Impulse response of the Channel - 12 kft 26AWG

Amplitude vs. time samples @ 2.2 MHz

Magnitude (dBm) vs. frequency (Hz)
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
    \[ \text{symbol} \otimes \text{channel} \Leftrightarrow \text{FFT(symbol)} \times \text{FFT(channel)} \]
  - Then division by the FFT(channel) can undo channel distortion

\[ \nu \text{ samples} \quad N \text{ samples} \]
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

![Diagram showing channel and shortened channel impulse responses](image)
Convolution Review

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

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

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

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

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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)
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

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