Asymmetrical Digital Subscriber Line (ADSL)
Asymmetrical Digital Subscriber Line

- Background
  - motivation for developing ADSL
  - historical development
- DSL end-to-end environment and reference model
- Line environment - characteristics of local loop (LL)
- Why conventional modems don’t work so well in LL?
- Modem technology in ADSL
- DSL flavors: ISDN (!), HDSL, ADSL, VDSL ...
- Standards
Motivation for developing ADSL

- Need for **high-speed Internet access** - also telephone modem speeds have peaked and cable modems have turned out
- DSL means methods to transmit **high speed data to local loop** by using unshielded 2-wire twisted pairs
- DSL allows rates varying from **160 kb/s up 50 Mb/s** on down link (DL) depending on technology used!
- In the most popular commercial ADSL 512 kbit/s upstream and 2048 kb/s downstream
- Different operation modes developed to serve symmetric and asymmetric traffic requirements and different rates (STM and ATM supported by ADSL)
History of digital access in PSTN

Through analog voice:
- Connecting a voice-band modem (as V.90)
- No switch or network infra changes

Through ISDN switch:
- Yields basic rate access (BRI)
- fixed throughput 2B+D
Digital access in PSTN (cont.)

- Using POTS splitters
  - POTS FDM splitters separate voice and DSL channels

- Using digital switch
  - Next generation intelligent switch recognizes subscriber devices and adjusts its HW parameters (PSTN telephone, voice-band modem, DSL modem)

Digital/analog switch

Requires new in-house wiring here
Comparing modem technologies

- Full ADSL
- G.lite ADSL
- ISDN
- 56K
- 28.8K
- 14.4K

Maximum Speed - Actual speed will vary
### Short history of ADSL

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
<td>Bell Labs discovers a new way to make traditional copper wires support new digital services - especially video-on-demand (VOD)</td>
</tr>
<tr>
<td>1990</td>
<td>Phone companies start deploying High-Speed DSL (HDSL) to offer T1 service on copper lines without the expense of installing repeaters - first between small exchanges</td>
</tr>
<tr>
<td>1990</td>
<td>Phone companies begin to promote HDSL for smaller and smaller companies and ADSL for home internet access</td>
</tr>
<tr>
<td>1993</td>
<td>Evaluation of three major technologies for ADSL: QAM, DMT and CAP</td>
</tr>
<tr>
<td>1995</td>
<td>Innovative companies begin to see ADSL as a way to meet the need for faster Internet access</td>
</tr>
<tr>
<td>1998</td>
<td>DMT was adopted by almost all vendors following ANSI T1.413 - issue 2 (in contrast to CAP)</td>
</tr>
<tr>
<td>1999</td>
<td>ITU-T produced UADSL G.992.2 (G.lite) and G.922.1 (G.full)</td>
</tr>
</tbody>
</table>
Generic DSL reference model

- **CO**: Central office
- **CP**: Customers premises - local loop connects to switch (CO)
- **TE**: Terminal equipment - PC or telephone
- **NT**: Network terminal - DSL modem at CP
- **NID**: Network interface device - all customer's installation reside right from this point and telephone company's to the left in the diagram
- **MDF**: Main distribution frame - wire cross-connection field connects all loops to CO
- **LT**: Line termination eg DSL modem
- **repeater**: signal regeneration for transmission introduced impairments
- **local loop**: in ADSL 2-wire connection between CO and CP
ADSL and ADSL-lite have the major difference in the missing **FDM splitter**

This causes lower rates for ADSL-lite but makes it cheaper to install
DSL access multiplexer (DSLAM)

- DSLAM provides access to LANs, WANs and other services
- DSLAM consists of
  - subscriber links (ATU-R to ATU-C)
  - connections to other DSL/broadband-circuits
  - interfaces to ISDN exchange
Using DSLAM
Using ADSL
What is specified in ADSL standard? **ANSI T1.413** ADSL reference model:

- Standard specifies **interfaces** and **units** as for example:
  - **ATU-R**: ADSL transceiver unit - remote terminal
  - **ATU-C**: ADSL transceiver unit - central office terminal
  - **U-C (2)**, **U-R (2)**

  **In T1.413 the V-C and T-R interfaces are defined only in terms of their functions but they are not technically specified.**
ADSL challenge: bad quality local loop cables

- **Attenuation**
- **Crosstalk**
  - Near-end crosstalk (NEXT) appears when same frequency band used for UL and DL - between A-A
  - Far-end crosstalk (FEXT) appears in the link A-B
- **Interference**: other lines, overlapping RF-spectra
- **Bridged taps, loading coils**
- **Weather**: conditions (moisture, temperature) affect crosstalk and line impedance
Modeling the loop cable

- Modeled as a transmission line.

![Circuit Diagram](image)

**Twisted-Pair Typical Parameters:**

- $R(f) = (1 + j)\sqrt{f/4} \ \Omega/\text{km}$ due to the skin effect
- $L = 0.6 \ \text{mH/km}$ (relatively constant above 100kHz)
- $C = 0.05 \ \mu\text{F/km}$ (relatively constant above 100kHz)
- $G = 0$
Cable attenuation

- Cable gain in dB is
  \[ H_{dB}(d, \omega) \approx -k_R \times d \times \sqrt{\omega} \]

- \( k_R \) — cable constant (typically 0.008)
- \( d \) — cable distance in km
- \( \omega \) — frequency in rad/s

- Attenuation in dB is proportional to cable length
  — 2x distance doubles attenuation in dB
  — reduce atten by using larger diameter cable

- Attenuation also proportional to root-frequency
  — 4x frequency doubles attenuation in dB
  — fast rolloff once attenuation reaches 20dB
DSL Data rates vrs distance

Practice ->

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>Line rate Mb/s assym</th>
<th>Line rate Mb/s symm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>50</td>
<td>22</td>
</tr>
<tr>
<td>0.9</td>
<td>30</td>
<td>13</td>
</tr>
<tr>
<td>1.2</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td>1.8</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>2.3</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>3.5</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

0.4 mm (26 AG) twisted pair

Capacity Cn of 100 m cables with W = 30 MHz

<table>
<thead>
<tr>
<th># Interferers</th>
<th>One interferer</th>
<th>24 interferer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable Category 3</td>
<td>136 Mb/s</td>
<td>79 Mb/s</td>
</tr>
<tr>
<td>Category 4</td>
<td>323 Mb/s</td>
<td>253 Mb/s</td>
</tr>
<tr>
<td>Category 5</td>
<td>386 Mb/s</td>
<td>316 Mb/s</td>
</tr>
</tbody>
</table>

<-Theory
ADSL meets local loop challenges

- Restricted bandwidth
  - careful allocation of bits for each sub-carrier
- Changing circumstances (whether, bridged taps)
  - Adaptive setup phase
- High attenuation
  - Usage of relatively high bandwidth for transmission
- Compatibility to old POTS
  - Own band for POTS by splitters
- Interference and cross-talk
  - Coding
  - Interleaving
  - Modulation (OFDM/DMT)
  - Echo cancellation

Note: loading coils must be removed from cables in order to ADSL to work
Reference: A baseband system
Modem parts

- Analog parts
  - analog transmit and receiver filters
  - DAC, automatic gain control, ADC
- Digital parts
  - modulation/demodulation
  - coding/decoding
    - Reed-Solomon
    - Trellis
  - bit packing/unpacking (compressed transmission)
  - framing
  - scrambling
Modem technology

- Conventional modem modules
  - Constellation mapping
  - Interleaving (convolutional)
  - Symbol/bit conversion
  - Timing recovery

- Advanced techniques for DSL
  - Carrierless AM/PM (CAP) or QAM line codes (97% of USA installations apply this method)
  - Fast Fourier Transforms for Discrete Multi-Tone Modulation (DMT) - the dominant method
    - tone ordering -> peak-to-average ratio (PAPR) decrease
    - channel equalization
    - water pouring bit allocations
    - guard intervals
  - Turbo - coding
  - Adaptive echo canceller
RADSL start-up phases

- RADSL (rate adaptive DSL) modems apply sophisticated **hand shaking** to initiate transmissions that include
  - **Activation**: notice the need for communications
  - **Gain setting/control**: Adjust the power for optimum transmission and minimum emission
  - **Synchronization**: Clocks and frames to the same phases
  - **Echo cancellation**
  - **Channel identification and equalization**.
- In DMT modulation during the handshaking active channels are decided and bit rates assigned for them
Multi-tone modulation (cont.)

- In channel activation phase different sub-channels are allocated for their optimum rates (by changing number of levels in modulation)
- DMT-ADSL supports both synchronous transfer mode (STM) and asynchronous transfer mode (ATM, AS0 used for primary cell stream)
- DMT defines **two data paths**: fast and interleaved
  - Fast
    - low latency (2ms)
    - real-time traffic
  - Interleaved
    - low error rate
    - Reed-Solomon encoding (convolutional codes) at the expense of increased latency
ADSL is based on OFDM/DMT

OFDM Transmitter

- Binary input
- Channel estimation
- Interleaving
- Modulation (QAM)
- Pilot insertion
- Serial to Parallel
- IFFT
- Parallel to serial
- Adding Guard interval
- Pulse shaping
- D/A
- RF Tx

OFDM Receiver

- Binary Output
- Error correction coding
- Interleaving
- Demodulation (QAM...)
- Channel Estimation
- Parallel to serial
- Deleting Guard interval
- Filter A/D
- Time and frequency Synchronisation
- RF Rx
Discrete multi-tone (DMT) modulation

- **ANSI T1.413** specifies DMT modem for ASDL applications
- **Downstream**:
  - 2.208 MHz sampling rate, 256 tones 0 … 1.104 MHz
  - Symbol rate 4000 symbols /s. Each sub-channel is 4.3 kHz wide
  - max rate 32 kb/s per channel (compare to V.90 modem)
- **Upstream**:
  - 275 kHz sampling rate, 32 tones 0 … 138 kHz

ASx: high-speed, downstream simplex nx1.54Mb/s
LSx: low-speed, duplex channels 160…576 kb/s
crc: cyclic redundancy check
FEC f,i: (fast, interleaved): forward error correction
scram f,i: scrambling
ATU-C: ADSL transmitter unit - central office
V-C interface

Reference points:
- Mux Data Frame
- FEC Output Data Frame

**ATU-C transmitter**
DMT spectra / ISDN linecodes

Sub-carrier spacing is 4.3125 kHz - 256 total sub-carriers

<table>
<thead>
<tr>
<th>Sub-carrier</th>
<th>Frequency</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0 Hz</td>
<td>DC-not used for data</td>
</tr>
<tr>
<td>5</td>
<td>25 kHz</td>
<td>lower limit for upstream data</td>
</tr>
<tr>
<td>18</td>
<td>80 kHz</td>
<td>Approx limit for 2B1Q ISDN</td>
</tr>
<tr>
<td>28</td>
<td>120 kHz</td>
<td>Approx. Limit for 4B3T ISDN</td>
</tr>
<tr>
<td>32</td>
<td>138 kHz</td>
<td>upper limit for upstream data</td>
</tr>
<tr>
<td>64</td>
<td>276 kHz</td>
<td>Pilot - not used for data</td>
</tr>
<tr>
<td>256</td>
<td>1104 kHz</td>
<td>Nyqvist - not used for data</td>
</tr>
</tbody>
</table>
ADSL system total data rate

- Total data rate = Net data rate + System overheads
- The net data rate is transmitted in the ADSL bearer channels
- ADSL system overheads
  - an ADSL embedded operations channel, eoc
  - an ADSL overhead control channel, aoc
  - crc check bytes
  - fixed indicator bits for O&M*
  - Reed-Solomon FEC redundancy bytes
- These data streams are organized into ADSL frames and super-frames for the downstream and upstream data

O&M: error detection, corrected errors, loss of signal, remote defects ...
ADSL frames

68 DMT data symbols, -> symbol rate ~4000/sec

- bearer channel allocation during initial setup determines ratio of interleaved and fast data frames (Nf,Ns)
- 8 crc bits (crc0-7) supervise fast data transmission
- 24 indicator bits (ib0-ib23) assigned for OAM functions

super frame boundary identification

superframe
(17 msec)

frame 0
frame 1
frame 2

frame 34
frame 35

frame 66
frame 67

Synch symbol

No user or bit-level data

(Note: i.b. = indicator bit)

frame (68/69 x 250 μsec)

Fast data buffer

Interleaved data buffer

Fast byte

Fast data

FEC Redundancy

(Interleaved data)

Kf bytes
(Mux data frame, point A))

Rdsf

Nf bytes

Ns bytes
(Constituent encoder input data frame, point C))

see next slide
Fast sync - byte

**EVEN NUMBERED FRAMES**

<table>
<thead>
<tr>
<th>Frames 0,1</th>
<th>Frames 2-33, Frames 36-67</th>
</tr>
</thead>
<tbody>
<tr>
<td>msb</td>
<td>lsb</td>
</tr>
<tr>
<td>crc7</td>
<td>crc6</td>
</tr>
<tr>
<td>crc5</td>
<td>crc4</td>
</tr>
<tr>
<td>crc3</td>
<td>crc2</td>
</tr>
<tr>
<td>crc1</td>
<td>crc0</td>
</tr>
<tr>
<td>ib15</td>
<td>ib14</td>
</tr>
<tr>
<td>ib13</td>
<td>ib12</td>
</tr>
<tr>
<td>ib11</td>
<td>ib10</td>
</tr>
<tr>
<td>ib9</td>
<td>ib8</td>
</tr>
<tr>
<td>eoc6</td>
<td>eoc5</td>
</tr>
<tr>
<td>eoc4</td>
<td>eoc3</td>
</tr>
<tr>
<td>eoc2</td>
<td>eoc1</td>
</tr>
<tr>
<td>r1</td>
<td>1</td>
</tr>
<tr>
<td>sc7</td>
<td>sc6</td>
</tr>
<tr>
<td>sc5</td>
<td>sc4</td>
</tr>
<tr>
<td>sc3</td>
<td>sc2</td>
</tr>
<tr>
<td>sc1</td>
<td>0</td>
</tr>
</tbody>
</table>

**ODD NUMBERED FRAMES**

<table>
<thead>
<tr>
<th>Frames 34,35</th>
<th>(immediately follow even-numbered frame to the left)</th>
<th>lsb</th>
</tr>
</thead>
<tbody>
<tr>
<td>msb</td>
<td>ib7</td>
<td>ib6</td>
</tr>
<tr>
<td>ib15</td>
<td>ib23</td>
<td>ib22</td>
</tr>
<tr>
<td>ib13</td>
<td>eoc13</td>
<td>eoc12</td>
</tr>
<tr>
<td>ib12</td>
<td>sc7</td>
<td>sc6</td>
</tr>
<tr>
<td>ib11</td>
<td>sc7</td>
<td>sc6</td>
</tr>
</tbody>
</table>

**crc:** cyclic redundancy check
**eoc:** embedded operations channel (O & M of ATU-C and ATU-R)
**ib:** indicator bits (O & M)
ATU-C transmitter reference model for STM* transport

Asx: any one of the simplex bearer channels AS0, AS1, AS2 or AS3
LSx: any one of the duplex bearer channels LS0, LS1 or LS2
NTR: Network Timing Reference: 8 kHz reference transmitted downstream
aoc: ADSL overhead control channel
eoc: embedded operations channel

*Synchronous transfer mode
xDSL- systems

- **HDSL -- High Bit Rate DSL**
  - 1.544 Mbps (T1) or 2.048 Mbps (E1) symmetrical
  - channel associated signaling
  - 2- or 4-wire connections
- **ADSL -- Asymmetric DSL**
  - up to 8 Mbps downstream and 640 Kbps upstream
  - ATM / STM compatible
  - 2-wire compatible
  - requires splitter and separate phone line from box to wall
- **CDSL -- Consumer DSL/ADSL-lite**
  - ATM (Q.2931) signaling only
  - up to 1.555 Mbps downstream and 512 Kbps upstream
  - reduced options, performance, cost, easy to install
**xDSL- systems (cont.)**

- **RDSL -- Rate-Adaptive DSL**
  - adjusts transmission rates in both directions to obtain the best speed under prevailing conditions
  - otherwise like ADSL
- **SDSL -- Symmetric DSL**
  - one pair of copper wire used, 774 kbps
  - channel associated signaling or Q.921
- **VDSL -- Very-High-Bit-Rate DSL**
  - speeds up to 13-52 Mbps DL, 1.5-2.3 Mbps UL, but for only short distances, applies ATM
**xBRI (cont.)**

- **BRI ISDN (DSL)**
  - uses existing ISDN equipment, but in 'always on' mode instead of as a dial-up service. Yields 2B+D
  - up to 128 kbps + 16 kbps or X.25 with 160 kbps
  - signaling Q.921/Q.931
  - designed for speech networks

- **V.90**
  - 56 kbps DL, 33.6 kbps UL
  - signaling analog
  - for speech network
## xDSL systems and applications

| xDSL                        | Asymmetric: Downstream: 1.5Mbps -> 8Mbps  
|                            | Upstream: 16Kbps -> 640Kbps  
|                            | Range: 5400 m - 1.544Mbps  
|                            | 4800 m - 2.048Mbps  
|                            | 3600 m - 6.312Mbps  
|                            | 2700 m - 8.448Mbps  
| ADSL Asymmetric Digital Subscriber Line | Internet access  
|                            | VoD and video access services  
|                            | Remote LAN access  
|                            | Interactive multimedia  
| VDSL Very High Data Rate Digital Subscriber Line | Asymmetric: Downstream: 13Mbps -> 52Mbps  
|                            | Upstream: 1.6Mbps -> 2.3Mbps  
|                            | Range: 1350 m - 12.96Mbps  
|                            | 900 m - 25.82Mbps  
|                            | 300 m - 51.84Mbps  
|                            | Same as ADSL and HDTV  

### xDSL systems compared (cont.)

<table>
<thead>
<tr>
<th>DSL</th>
<th>Digital Subscriber Line</th>
<th>ISDN service</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Duplex: 160K (2B+D+Management)</td>
<td>Voice and data communications</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HDSL</th>
<th>High Data Rate Digital Subscriber Line</th>
<th>T.1 and E.1 service</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Duplex: 2 x T.1 (1.544Mbps) / 2 x E.1 (2.048Mbps)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 to 4 pairs of copper-wire</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Range: 3600 meter</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SDSL</th>
<th>Single Line Digital Subscriber Line</th>
<th>Premises access for synchronous services</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Duplex: 2 x T.1 (1.544Mbps) / 2 x E.1 (2.048Mbps)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 pair of copper-wire</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Range: 3000 meter</td>
<td></td>
</tr>
</tbody>
</table>
Standards

Hierarchy of standards

International level
-examples: ITU: International Telecommunications Union - yields recommendations that may be adapted by companies

Regional/national level
-examples: ANSI (American Standards Institute) /ETSI (European Technical Standards Institute)

Multi-corporate level
-examples: ADSL forum/ATM forum

Corporate level
-open or proprietary standard created by a company

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See also:
http://www.ktl.com/testing/telecoms/xdsl-standards.htm
Peak to T1.413 table of contents

4 Reference models 9
4.1 System reference model 9
4.2 ATU-C transmitter reference models 10
  4.2.1 ATU-C transmitter reference model for STM transport 10
  4.2.2 ATU-C transmitter reference model for ATM transport 11
4.3 ATU-R transmitter reference models 12
  4.3.1 ATU-R transmitter reference model for STM transport 12
  4.3.2 ATU-R transmitter reference model for ATM transport 13

5 Transport capacity 14
5.1 Transport of STM data 14
5.2 Transport of ATM data 15
5.3 ADSL system overheads and total data rates 16
5.4 Classification by ATU options 18

6 ATU-C functional characteristics 19
6.1 STM Transmission Protocol Specific functionalities 19
  6.1.1 ATU-C input and output V-C interfaces for STM transport 19
  6.1.2 Downstream simplex bearer channels – bit rates 19
  6.1.3 Downstream/upstream duplex bearer channels – bit rates 19
  6.1.4 Payload transfer delay 20
  6.1.5 Framing structure for STM transport 20
6.2 ATM Transport Protocol Specific functionalities 20
  6.2.1 ATU-C input and output V-C interface for ATM transport 20
  6.2.2 Payload transfer delay 21
6.3 Network timing reference
   6.3.1 Need for NTR
   6.3.2 Transport of the NTR
   6.3.3 Accuracy requirements
6.4 Framing
   6.4.1 Data symbols
   6.4.2 Synchronization
   6.4.3 Reduced overhead framing
6.5 Scramblers
6.6 Forward error correction
   6.6.1 Reed-Solomon coding
   6.6.2 Interleaving
   6.6.3 Support of higher downstream bit rates with S=1/2
6.7 Tone ordering
6.8 Constellation encoder (with trellis coding)
   6.8.1 Bit extraction
   6.8.2 Bit conversion
   6.8.3 Coset partition and trellis diagram
6.8.4 Constellation encoder
6.9 Constellation encoder (without trellis coding)
   6.9.1 Bit extraction
   6.9.2 Constellation encoder
6.10 Gain scaling
6.11 Modulation
References

- ANSI T1.413, issue 2 standard