xDSL Technology and Applications: Removing the Telephone Line Bottleneck

Krista S. Jacobsen
Texas Instruments
Broadband Access Group
jacobsen@ti.com
Overview/Goals

- Introduction
- DSL network topology
- Transmission environment
- Line code alternatives
- ADSL
- Splitterless ADSL and G.lite
- VDSL
- Spectral compatibility
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADSL:</td>
<td>Asymmetric digital subscriber lines</td>
</tr>
<tr>
<td>CO:</td>
<td>Central office</td>
</tr>
<tr>
<td>DSL:</td>
<td>Digital subscriber line(s)</td>
</tr>
<tr>
<td>HDSL:</td>
<td>High-speed digital subscriber lines</td>
</tr>
<tr>
<td>ISDN:</td>
<td>Integrated services digital network</td>
</tr>
<tr>
<td>ONU:</td>
<td>Optical network unit</td>
</tr>
<tr>
<td>POTS:</td>
<td>Plain old telephone service</td>
</tr>
<tr>
<td>SDSL:</td>
<td>Symmetric digital subscriber lines</td>
</tr>
<tr>
<td>VDSL:</td>
<td>Very high-speed digital subscriber lines</td>
</tr>
</tbody>
</table>
## Overview of xDSL Flavors

<table>
<thead>
<tr>
<th>Technology</th>
<th>Data rates</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISDN</td>
<td>64+ kbps symmetric</td>
<td>Data transmission</td>
</tr>
<tr>
<td>HDSL</td>
<td>1.054/2.044 Mbps symmetric</td>
<td>2-pair repeaterless T1/E1</td>
</tr>
<tr>
<td>HDSL-2</td>
<td>1.054/2.044 Mbps symmetric</td>
<td>Single-pair T1/E1</td>
</tr>
<tr>
<td>SDSL</td>
<td>Under discussion…</td>
<td>Multiple HDSL, data transmission</td>
</tr>
<tr>
<td>ADSL</td>
<td>Up to 8 Mbps downstream</td>
<td>Internet, video, multimedia</td>
</tr>
<tr>
<td></td>
<td>Up to 800 kbps upstream</td>
<td></td>
</tr>
<tr>
<td>VDSL</td>
<td>Up to 52 Mbps downstream</td>
<td>Same as ADSL, but more of it</td>
</tr>
<tr>
<td></td>
<td>Up to 26 Mbps upstream</td>
<td></td>
</tr>
</tbody>
</table>
Digital Subscriber Lines (DSL)

Network Topology
The Local Loop

Local loop characteristics:

- The local loop has been designed solely to support voice traffic
- The 0-4 kHz bandwidth limitations of the local loop are a result of filters placed at the central office to help condition lines for voice traffic
- If the filters are removed, the local loop can support much higher data rates than voice band modems provide
- Achievable data rates depend on:
  - Loop length (attenuation)
  - Condition of line (bridged taps, loading coils, in-home wiring, etc.)
  - Noise (crosstalk, impulse noise, radio-frequency ingress)
Issues:

- Bandwidth limited by the local loop (POTS/ISDN - 56 kbps/128 kbps)
- Data traffic is congesting the voice network
  - Voice network designed around 3-6 minute average call
  - Data connections typically last over 20 minutes
**Issues:**

- *Removes local loop bottleneck*
  - Still have bandwidth limitations in the data network that must be addressed
- *Relieves congestion of voice network*
  - But analyst projections still show analog modems dominating until 2000+
Digital Subscriber Lines (DSL)

Transmission Environment
FACT:
Telephone networks were deployed to transfer analog voice signals, not high-speed digital signals.

RESULT:
Numerous impairments impede transmission in the frequency band beyond the voice band.
Environmental Variables

- Channel attenuation varies with:
  - length
  - gauge
  - frequency
  - bridged taps

- Various noises also impede high-speed transmission:
  - crosstalk
  - impulse noise
  - radio-frequency ingress

- Channel and noise characteristics vary substantially from line to line
Twisted-pair Channels

![Graph showing attenuation vs. frequency for different cable lengths and gauge sizes.](image)
Bridged Taps

- Uterminated stubs of twisted-pair cable connected in shunt to main pair
  - Originally used to provide for future plant expansion
  - No longer used
- Effect is notches/ripple in frequency spectrum
Effects of Bridged Taps
Crosstalk

- **Copper twisted pairs are grouped in binders**
  Up to 50 twisted pair per binder

- **Crosstalk**
  Caused by other pairs in the binder carrying xDSL, ISDN, T1, etc.
  Pairs in adjacent binders can also cause crosstalk
  Coupling (interference) increases with frequency

Near-end crosstalk (NEXT)

T1 Line

T1 Line

xDSL Line

Far-end crosstalk (FEXT)

T1 Line

xDSL Line

xDSL lines

T1 lines

POTS
Crosstalk Examples

![Crosstalk Examples Graph]

- **Power Density (dBm/Hz)**
- **Frequency**
  - 0 Hz
  - 500 kHz
  - 1.0 MHz
  - 1.5 MHz

- **24 HDSL NEXT**
- **24 ISDN NEXT**
- **1 T1 NEXT**
Radio-frequency Ingress

- Occurs when over-the-air signals couple into xDSL lines
  - AM radio
  - Amateur radio
Radio-frequency Ingress

- AM interferers are localized in frequency, maintain constant power with time
- HAM interferers are unpredictable
  - on/off keying
  - hopping in frequency
  - may be high or low power
- Strength of interferer depends on proximity of source to line
Impulse Noise

- Caused by home appliances, lightning, power line discharges, other unidentified sources
- Usually short-duration, high-power, fairly constant with frequency
- Can be 10’s of millivolts, 100’s of microseconds
Not an environment conducive to high-speed communication...
Digital Subscriber Lines (DSL)

Line Code Alternatives
Two Linecode Classes

◆ Single-carrier
  Spreads information content during each symbol over entire channel bandwidth
  ■ Examples:
    ✦ Carrierless Amplitude/Phase (CAP) Modulation
    ✦ Quadrature Amplitude Modulation (QAM)

◆ Multi-carrier
  Divides bandwidth into subchannels, allocates only some portion of the entire information content to each subchannel during each symbol
  ■ Examples:
    ✦ Discrete Multi-Tone (DMT) Modulation
    ✦ Discrete Wavelet Multi-Tone (DWMT) Modulation
Discrete Multi-Tone (DMT) Modulation

- Uses an inverse discrete Fourier transform (IDFT) to partition transmission bandwidth into subchannels
- Measures signal-to-noise ratio (SNR) of each subchannel and assigns data accordingly
  - Adapts to each line at start-up and automatically avoids severely degraded regions of bandwidth
  - Maximizes bit rate
  - Adapts during steady-state to maintain bit rate and noise margin

![Chart](chart.png)
Bit Allocation Example
Conceptual View of DMT

Power spectra of individual subcarriers

Composite DMT power spectrum
CAP and QAM are similar
- **QAM generates in-phase (I) and quadrature (Q) signals using sine/cosine mixer in analog domain**
- **CAP generates I and Q signals in the digital domain**

CAP/QAM symbols are short-duration, occupy entire available bandwidth
- Because the information is distributed evenly over the entire channel bandwidth, effects of channel impairments and noise must be overcome by transmit filters and equalizing receivers
**DMT vs. CAP/QAM**

- **DMT dynamically adapts to the conditions of the line**

- **CAP/QAM require highly-flexible, potentially complex filters to enable the receiver to dig out the signal**

The bit distribution cannot be varied across the frequency band.

Bit distribution varies based on channel and noise characteristics.
Digital Subscriber Lines (DSL)

Asymmetric Digital Subscriber Lines (ADSL)
**ADSL Basics**

- Standard-compliant ADSL uses DMT
- Supports asymmetric data rates
  - Distance and line condition dependent
    - Upstream data rates: up to 800 kbps
    - Downstream data rates: up to 8 Mbps
  - 10:1 downstream-to-upstream ratio
    - Ideal for Internet traffic (TCP/IP)
    - Ideal for MPEG movies
- Supports limited symmetric data rates
  - Up to ~ 800 Kbps
- Co-exists with life-line POTS service
  - Uses existing POTS infrastructure
ADSL Deployment

video switch

ADSL Access Mux (bridge)

ADSL ADSL ADSL

POTS (or ISDN) Switch

internet

CO

split

8 Mbps

800 kbps

ATM or 10BT/422

ADSL

split

ADSL

Texas Instruments
ADSL Data Rates and Ranges

Central Office

Downstream

Distance (kft)

Downstream data rate vs. distance from CO

Mbits/sec

26-gauge

24-gauge
ADSL Duplexing Alternatives

FDM (frequency division multiplexing)
- Upstream and downstream channels are disjoint in frequency
- Frequency separation of the two channels is easy to implement

Echo cancellation
- Upstream and downstream channels overlap in frequency
  - Echo canceler is used to separate channels
- Better performance than FDM
  - Downstream channel also uses higher-quality lower-frequency portions of the spectrum
Digital Subscriber Lines (DSL)

Splitterless ADSL and G.lite
A splitter is a cross-over filter that separates voiceband signals from passband DSL signals.

Splitters ease DSL implementation and allow coexistence of POTS and high-rate DSL on the same line.
Why Eliminate the Splitter?

TRUCK-ROLL = $$

- **Original DSL Application: Video-on-demand**
  - Constant bit rate service
  - Requires POTS splitter to satisfy service requirements over broad range of conditions and service areas

- **Latest DSL Application: Internet Access**
  - Variable-bit rate service
  - Allows retransmission of corrupted data
  - Elimination of splitter reduces costs, but also reduces data rate slightly
**Splitterless DSL Challenge**

**ON-HOOK**
- Impedance: $Z_1$
- Echo: ~Linear

**OFF-HOOK**
- Impedance $Z_2$
- Echo: Partially nonlinear
  - nonlinear components in some phones
  - inband AND out-of-band energy

Also have transient problems when transitioning from on-hook to off-hook state
What is G.lite?

- Intended for consumer mass market
  - Low cost/complexity
- Goal is easy installation
  - Minimize wiring changes
  - Avoid POTS splitter (splitterless)
- POTS and G.lite operate simultaneously
- Provide maximum coverage of customers
  - Reach more important than data rate
- Ensure spectral compatibility with standardized xDSL
## Comparison of Full-rate and G.lite

<table>
<thead>
<tr>
<th>Full rate (G.dmt, T1413i2)</th>
<th>U-ADSL (G.lite, UAWG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimized for data rate</td>
<td>Optimized for cost</td>
</tr>
<tr>
<td>8 Mbps/800Kbps</td>
<td>1.5Mbps/512 Kbps</td>
</tr>
<tr>
<td>256 tones</td>
<td>128 tones</td>
</tr>
<tr>
<td>15 bits per tone</td>
<td>8 bits per tone</td>
</tr>
<tr>
<td>Echo Canceled (EC)</td>
<td>FDM with EC option</td>
</tr>
<tr>
<td>Full initialization</td>
<td>Fast retrain</td>
</tr>
<tr>
<td>Not included</td>
<td>Power management</td>
</tr>
</tbody>
</table>
G.lite Customer Installation Options

**Splitterless installation**

**Distributed Splitter installation**

**Splittered installation**
Digital Subscriber Lines (DSL)

Very High-Speed Digital Subscriber Lines (VDSL)
Classic VDSL

- Intended for loops up to 4.5 kft (1.5 km) long
  - “Fiber-to-the-neighborhood”
  - “Last mile”
- Uses a much wider bandwidth than ADSL
  - Appropriate bandwidth depends on loop length
  - 10-12 MHz allows high bit rate transmission on a wide range of loop lengths
  - Very short loops (< 1 kft or 300 m) require even larger bandwidth to maximize performance
- VDSL may be deployed from the CO or local exchange (LEX) or from the ONU
VDSL ONU Deployment

- Likely deployment in rural or less densely populated areas
  - Both VDSL size and power consumption must be minimized: the ONU is small and its environment is uncontrolled

- ADSL lines may be in the same binder as VDSL lines emanating from the ONU
  - Spectral compatibility with ADSL an issue
VDSL CO/LEX Deployment

- Likely deployment in densely populated areas
  - Minimizing VDSL size and power consumption is important but not critical because the CO/LEX environment is controlled

- ADSL lines may also emanate from the CO/LEX
  - In this case VDSL never affects ADSL performance

Twisted-pair lines

CO/LEX

Up to 4.5 kft (1.5 km)
**VDSL System Requirements**

- Must be robust to common VDSL impairments
  - Bridged taps, crosstalk, radio-frequency (RF) ingress, impulse noise

- Must support both symmetric and asymmetric bit rates and a variety of asymmetric ratios
  - Symmetric: 26 Mbps, 13 Mbps, 8 Mbps, etc.
  - Asymmetric: 52/6.4 Mbps, 26/3.2 Mbps, 12/2 Mbps, 6/2 Mbps, etc.
  - Ratios: 8:1, 6:1, 4:1, 3:1, 2:1

- Must be spectrally compatible with ADSL and other services

- Low power consumption (1.5 W/line) and small size required for ONU deployment

- Low cost also desirable
**VDSL Egress Control**

- Inverse of ingress is egress
- Emissions from VDSL lines into amateur radio bands will occur if VDSL PSD is too high in those bands
- The VDSL PSD must be limited to -80 dBm/Hz within the amateur radio bands to ensure interference is inaudible
**Frequency-division duplexing (FDD)**

Inflexible/Expensive:

- in general, bandwidths of upstream and downstream channels must be determined in advance
- to accommodate different downstream:upstream bit rate ratios, channel bandwidths must be programmable, which leads to increases in system complexity
**Echo-cancellation (EC)**

**Impractical:**
- self-NEXT increases with frequency, so echo-cancellation is only practical over small, low-frequency bandwidths.
- Support of symmetric bit rate ratios is infeasible because required overlapping bandwidth is too high.
Time-division Duplexing (TDD)

- A single frequency band is used to support both upstream and downstream transmission
- Modems can either transmit or receive at any time, but not both simultaneously
- Modems in a binder are synchronized to a common clock
- A superframe structure is used to coordinate when the VTU-Os and VTU-Rs transmit
- **Synchronized DMT (SDMT)** = DMT modems operating in a TDD fashion
A superframe is a set of consecutive symbols, each of which is classified as downstream, upstream, or quiet.

By varying the number of upstream and downstream symbols in the superframe, a wide range of data rate ratios can be supported.

**Example**: 20-symbol superframe
- 9-Q-9-Q superframe supports symmetric transmission
- 16-Q-2-Q superframe supports 8:1 transmission
- 12-Q-6-Q superframe supports 2:1 transmission

Ideally, all lines in a binder support the same data rate ratio.
Synchronization Requirements

- Superframes from different modems must be synchronized to avoid NEXT between lines
- Synchronization can be achieved by:
  - Providing a common clock at the ONU/CO (i.e., 8 kHz network clock)
  - Allowing one VTU-O to source the master clock for all lines
  - Using GPS technology to derive a common clock
Digital Subscriber Lines (DSL)

Spectral Compatibility
Bandwidth Utilization

Pre xDSL

Post xDSL

POTS

ADSL

ISDN

HDSL

VDSL
In this configuration, VDSL can interfere with ADSL

If band below 1.104 MHz supports upstream VDSL, then ADSL downstream performance is degraded by VDSL NEXT

If band below 1.104 MHz supports downstream VDSL, then ADSL downstream performance is degraded by VDSL FEXT

SDMT can prevent interference to ADSL band by turning off subchannels below 1.104 MHz

In situations when interference from VDSL to ADSL is not of concern, this band can be enabled to maximize performance
Summary

- Reviewed xDSL network topologies and associated issues
- Described transmission environment and channel impairments
  - xDSL environment is harsh
- Examined line code alternatives
  - DMT
  - CAP/QAM
- Described xDSLs:
  - ADSL
  - Splitterless
  - G.lite
  - VDSL