Signal Processing in Communications I: xDSL

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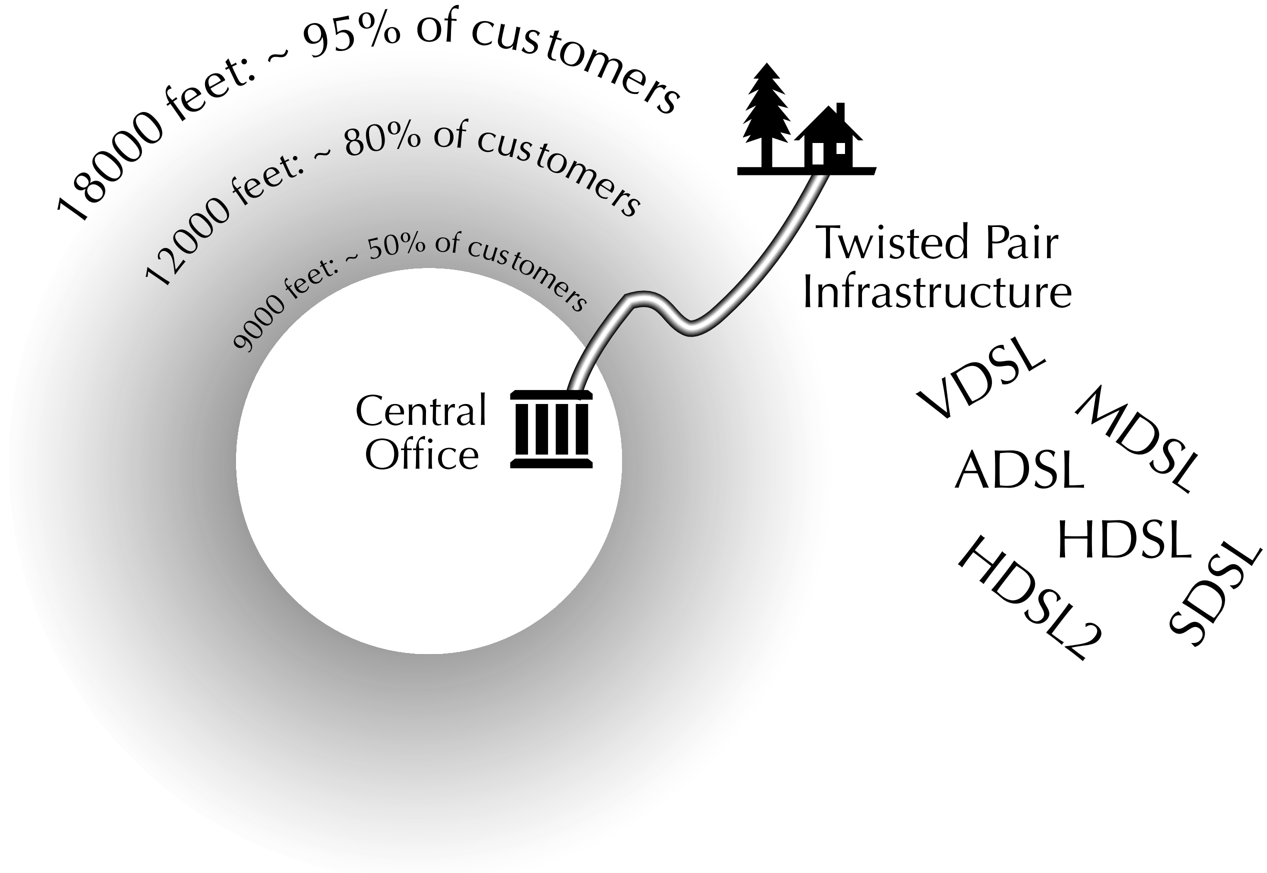
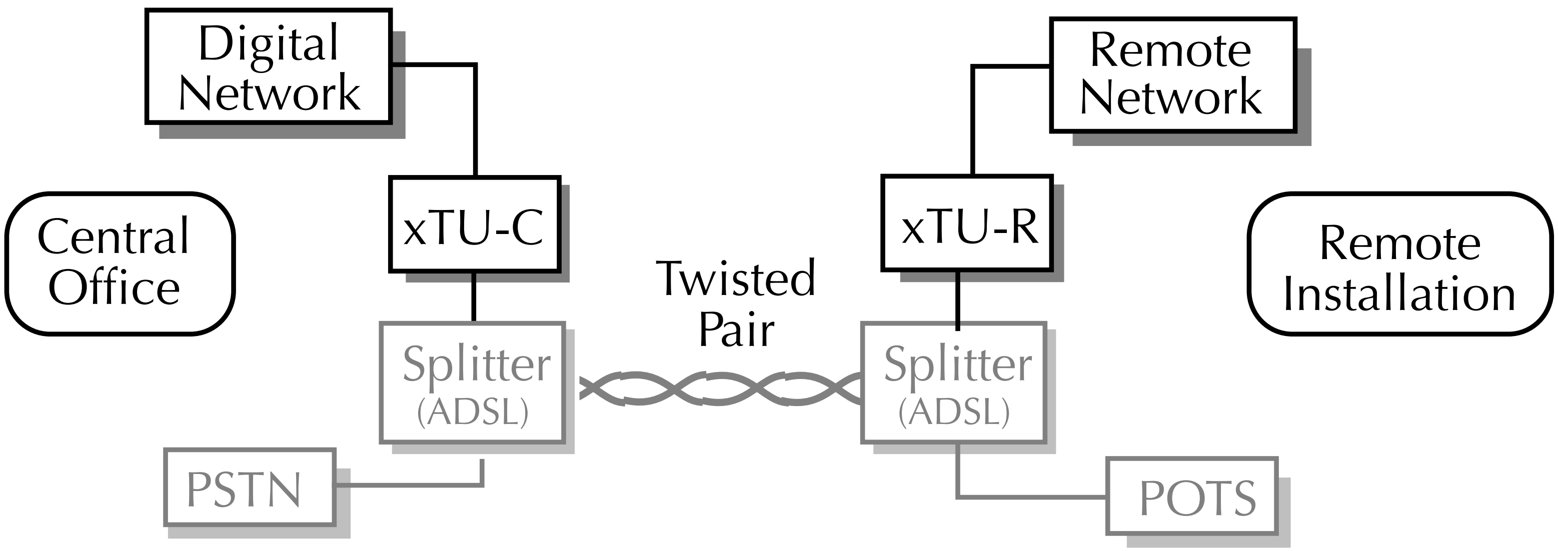
xDSL: Broadband over Twisted Pair



- xDSL: the delivery of high-speed digital data over twisted-pair local loop infrastructure
- An “Alphabet Soup” of xDSL services

Goals of xDSL Signal Processing



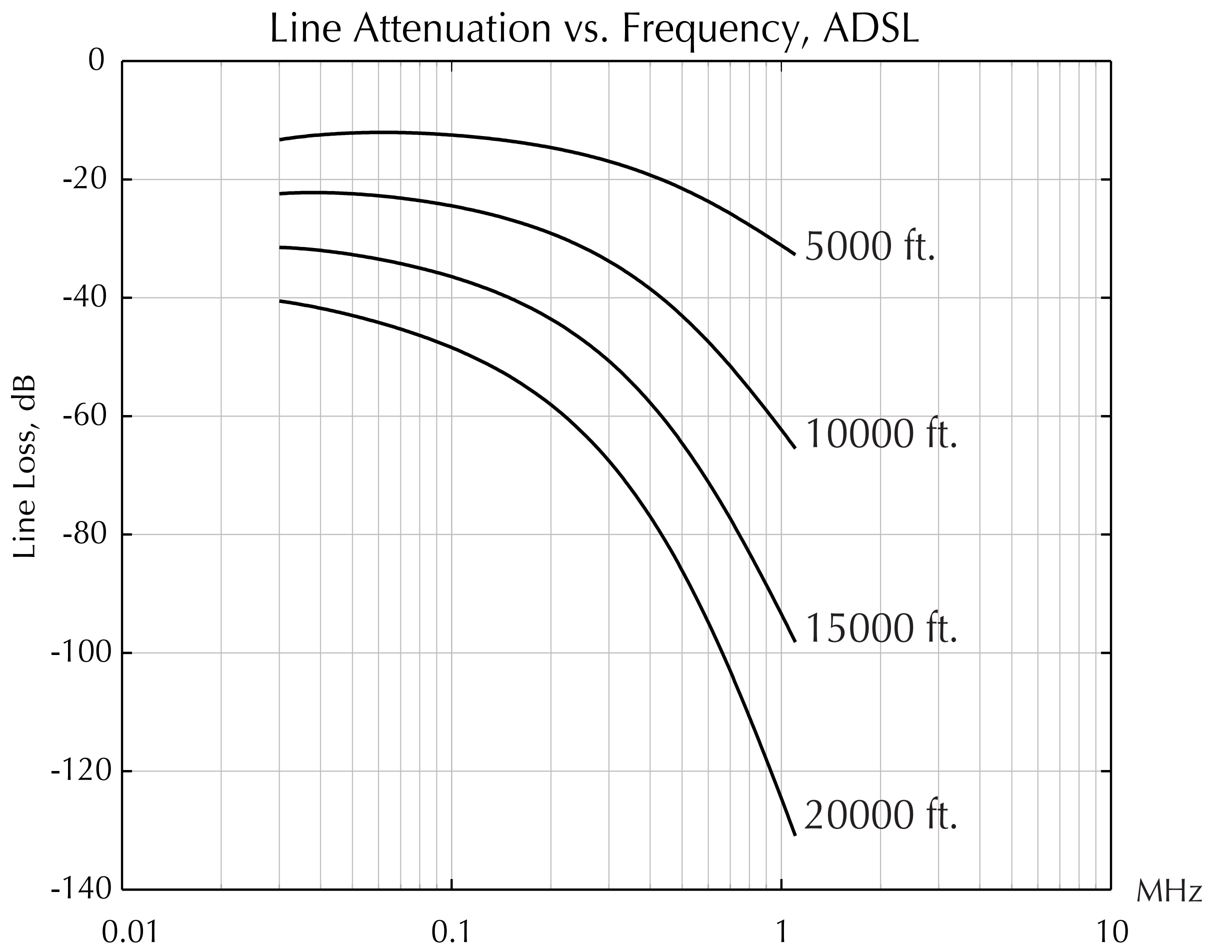
- As in voiceband modems, “evolution” in signal processing
- Performance
  - Highest data rate
  - Longest loop possible (reach)
- Cost
  - Two-pair vs. one-pair
  - Repeatered
  - Line conditioning

Outline

- The Twisted-Pair Transmission Environment
- High-Bit-Rate Digital Subscriber Line (HDSL)
- Asymmetric Digital Subscriber Line (ADSL)
- Some Future xDSL Systems
    - HDSL2
    - Very High-Bit-Rate Digital Subscriber Line (VDSL)
- Conclusions

Twisted Pair: Transmission Environment

- Channel Frequency Response

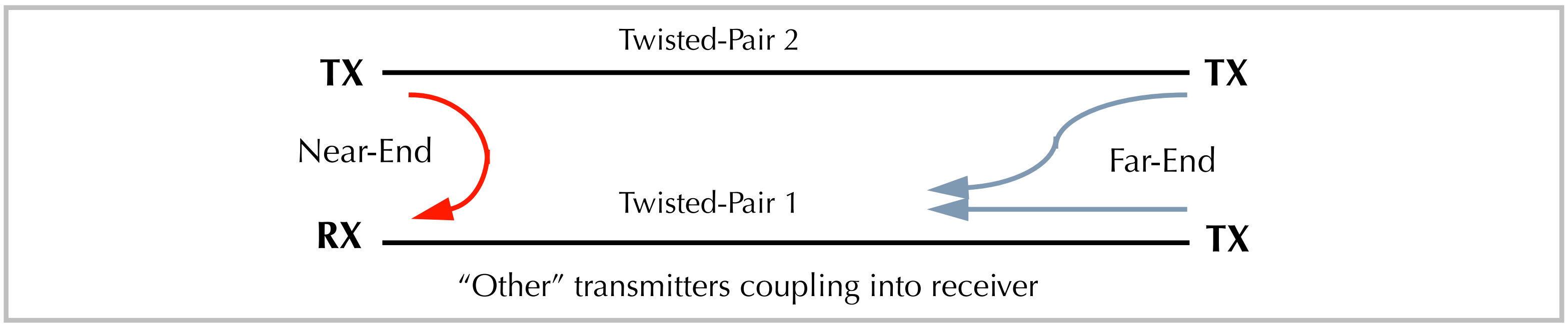


- Channel Background Thermal Noise: -140 dBm/Hz

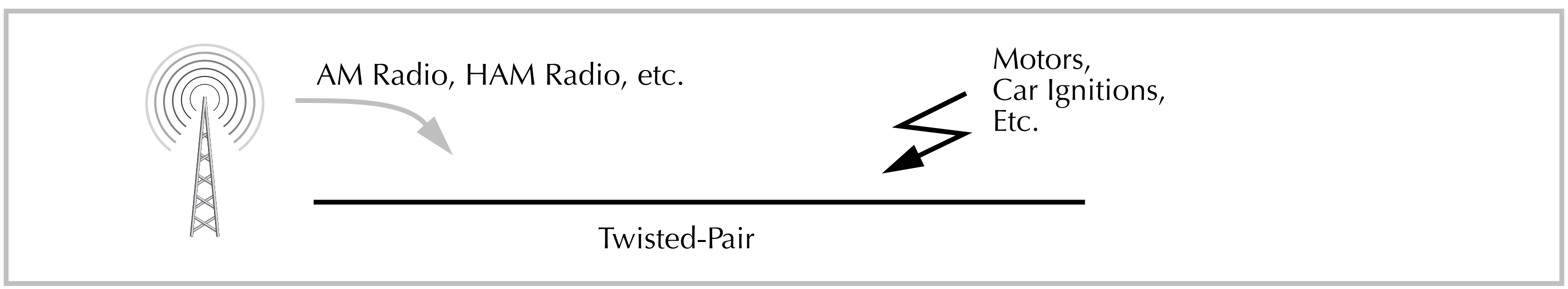
Twisted Pair: Other Impairments

Bridged Taps

Near-End/Far-End Crosstalk (NEXT/FEXT)



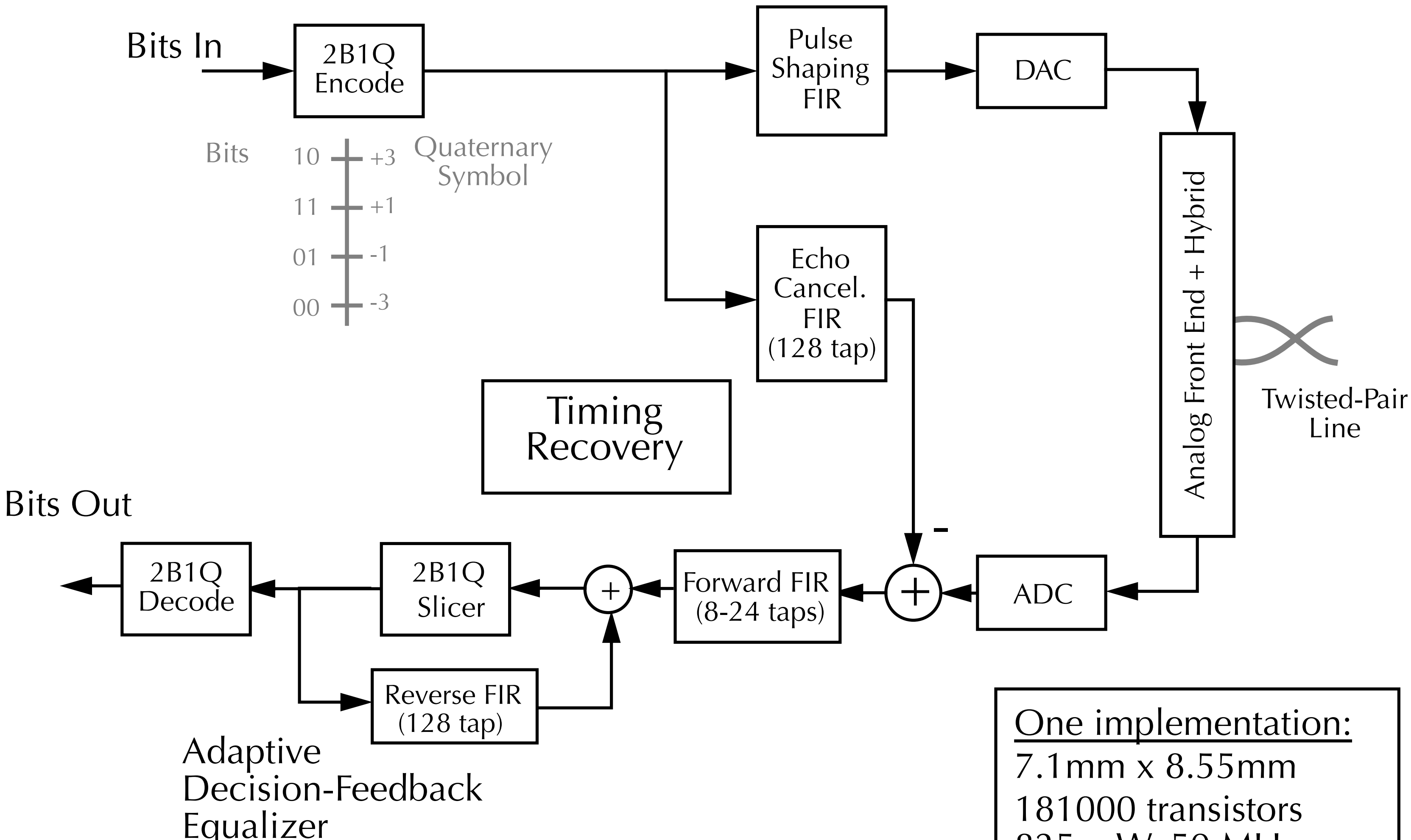
RF Ingress/Impulse Noise



High-Speed Digital Subscriber Line (HDSL)

- “Successor” to T1/E1
- Data transmission
  - DS1/T1: 1.544 Mbps
  - 12 kft, 24 gauge
  - 768 kbps duplex per pair, two pairs
  - Repeatered beyond 12 kft
- Transceiver:
  - Dual-duplex
  - Echo-cancelled
  - Linear 2B1Q modulation, 196 kHz bandwidth

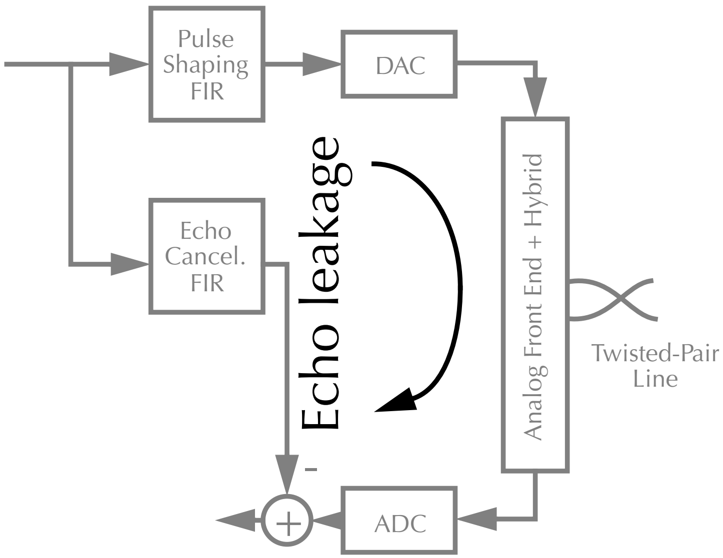
Basic HDSL Transceiver



One implementation:
7.1mm x 8.55mm
181000 transistors
825 mW, 50 MHz
[PairGain93]

HDSL Echo Cancellation

- Fully-overlapped spectrum between TX and RX - need to cancel echo response (hybrid leakage)



<u>Hybrid leakage - function of:</u>
Mismatch parasitics in hybrid
Impedance of loop vs. frequency
"Compromise" hybrid

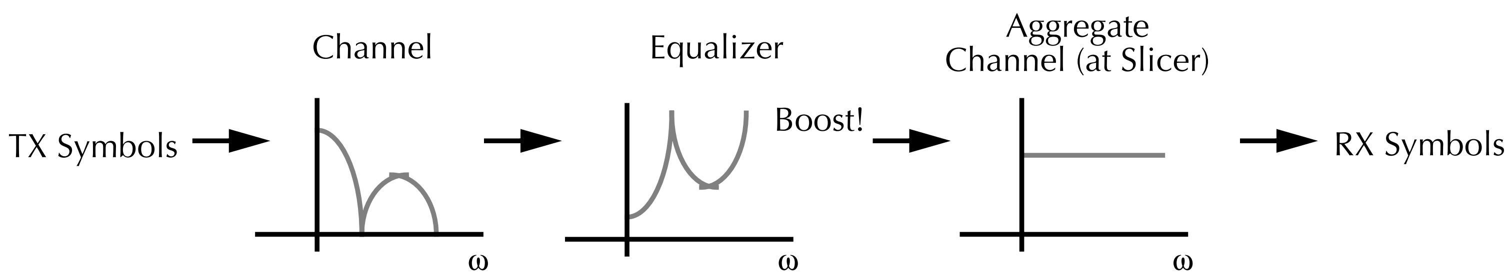
<u>Echo cancel FIR response includes:</u>
Analog TX/RX filter response
Transformer
Hybrid leakage

- Echo cancellation FIR adapted at startup
- Echo path impulse response typically time-limited to ~280 usec

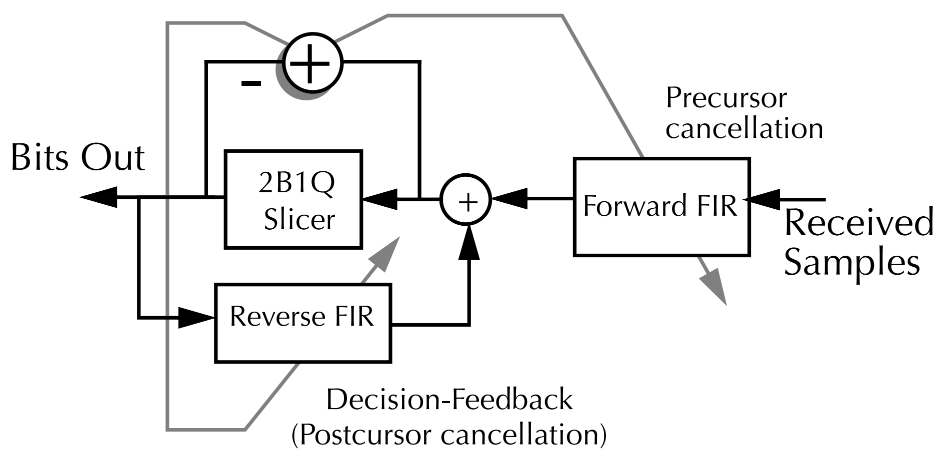
-> Typical FIR filter size: ~128 taps for baud sampling (400 kHz)

HDSL Equalization

- Need to minimize intersymbol interference at slicer
- Employ zero-forcing equalization:



- However, noise enhancement is a problem:
  use decision-feedback equalization



Most ISI is postcursor:
At baud rate:
8-tap forward FIR
128-tap reverse FIR

Asymmetric Digital Subscriber Line (ADSL)

- Intended for consumer deployment

- Asymmetric data transmission

  Rate Adaptive: "Best effort" on a given loop:

  (up to 8 Mbps downstream, 800 kbps upstream)

  Single-pair, repeaterless

- Transceiver:

  Full-duplex

  Echo-cancelled or frequency-division

  Discrete Multitone Modulation

  Coexistence with POTS

- Two flavors of ADSL

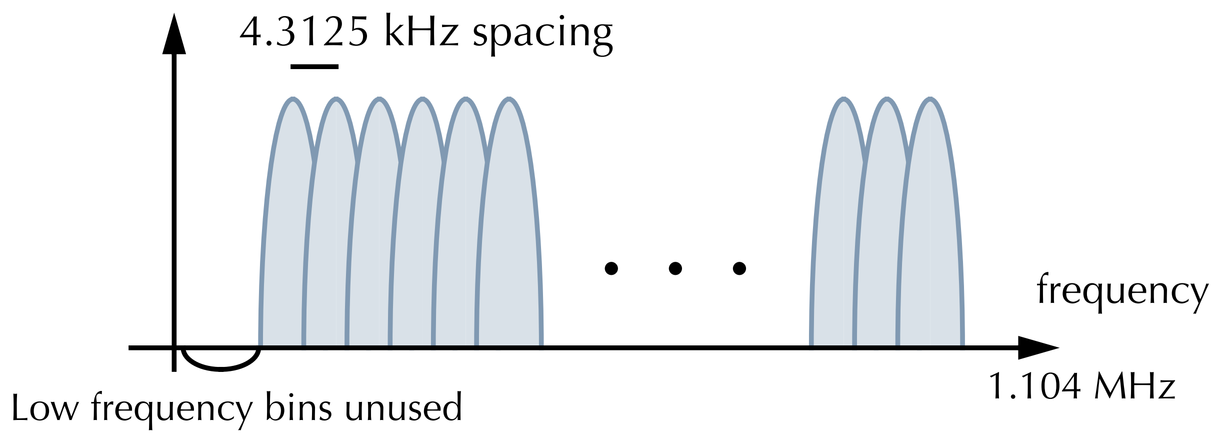
  g.dmt (g.992.1): "full" ADSL

  g.lite (g.992.2): "splitterless, low-cost, rate-limited"

  (1.544 Mbps peak downstream)

Discrete Multitone Modulation (DMT)

- Idea: separate information across narrow channels (or "bins"), with 256 (downstream) or 32 (upstream) possible bins.



- Optimize QAM constellation size for each bin based on SNR ("automatically" rate/margin adaptive)
- Symbol time is very slow: (~ 250 usec for ADSL); bits/symbol is *huge*

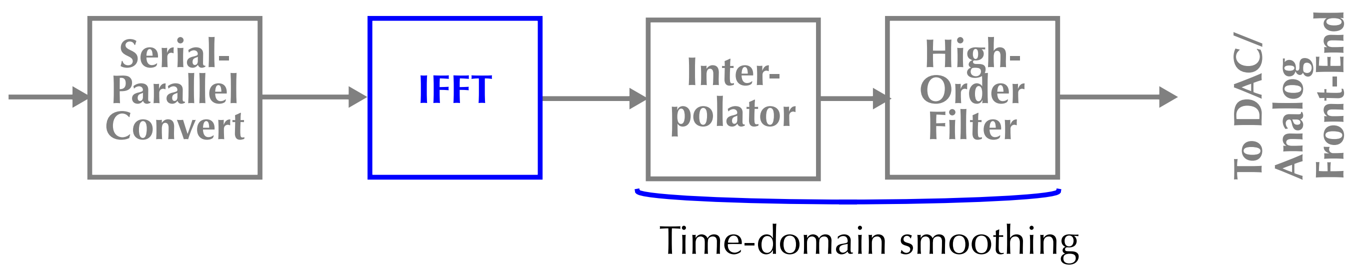
Can theoretically deliver payload near the Shannon capacity!

“Prototype” DMT Transceiver

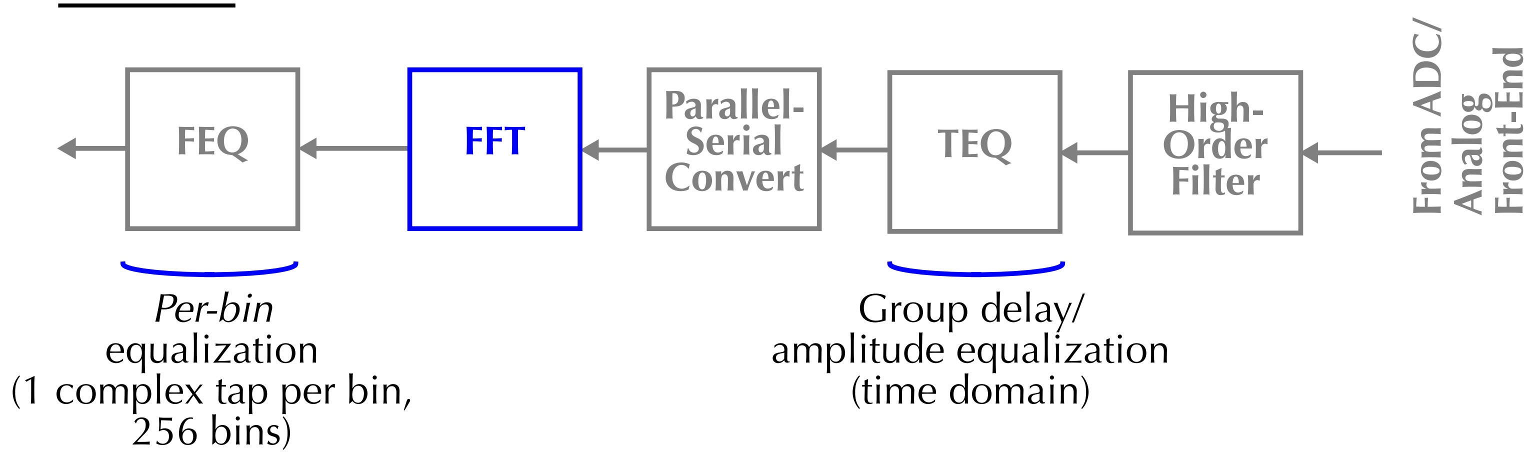
- Leverage off of massive DSP capability

  Signal synthesis is done entirely via FFT/IFFT engines

Transmitter



Receiver

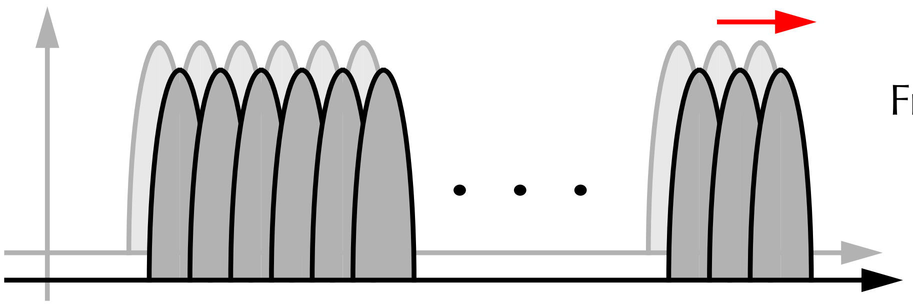


Some Key Issues....

- Timing recovery / Frequency accuracy

  Intersymbol interference in the *frequency* domain

  Expend downstream bin 64 (276 kHz) as pilot timing tone



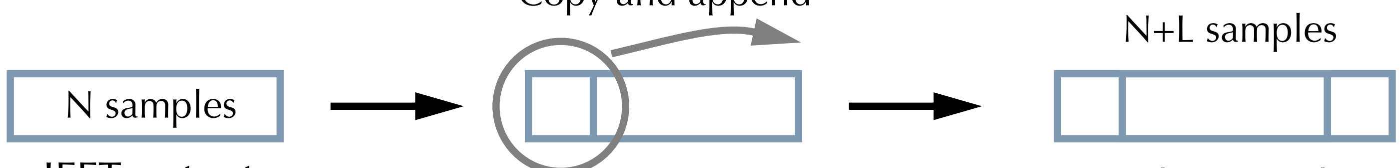
Frequency error in receiver results in "shift" of bins

- Cyclic prefix

  Append L samples of the IFFT TX output

  Serves as guard time against intersymbol interference

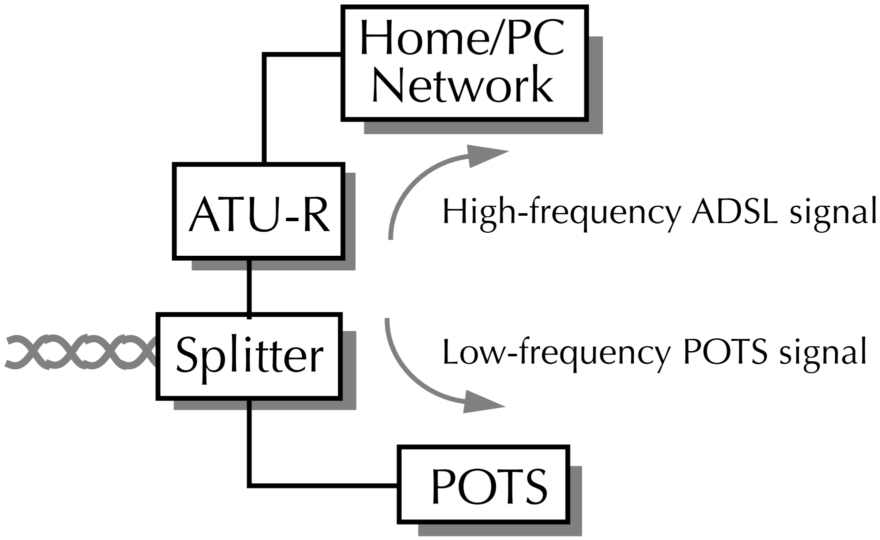
  Equalization via FFT requires *circular* convolution



Some Key Issues.... (cont)

- Splitterless vs. Splittered

  Full rate *g.dmt* requires splitter at remote to minimize interference between ADSL and POTS bands.



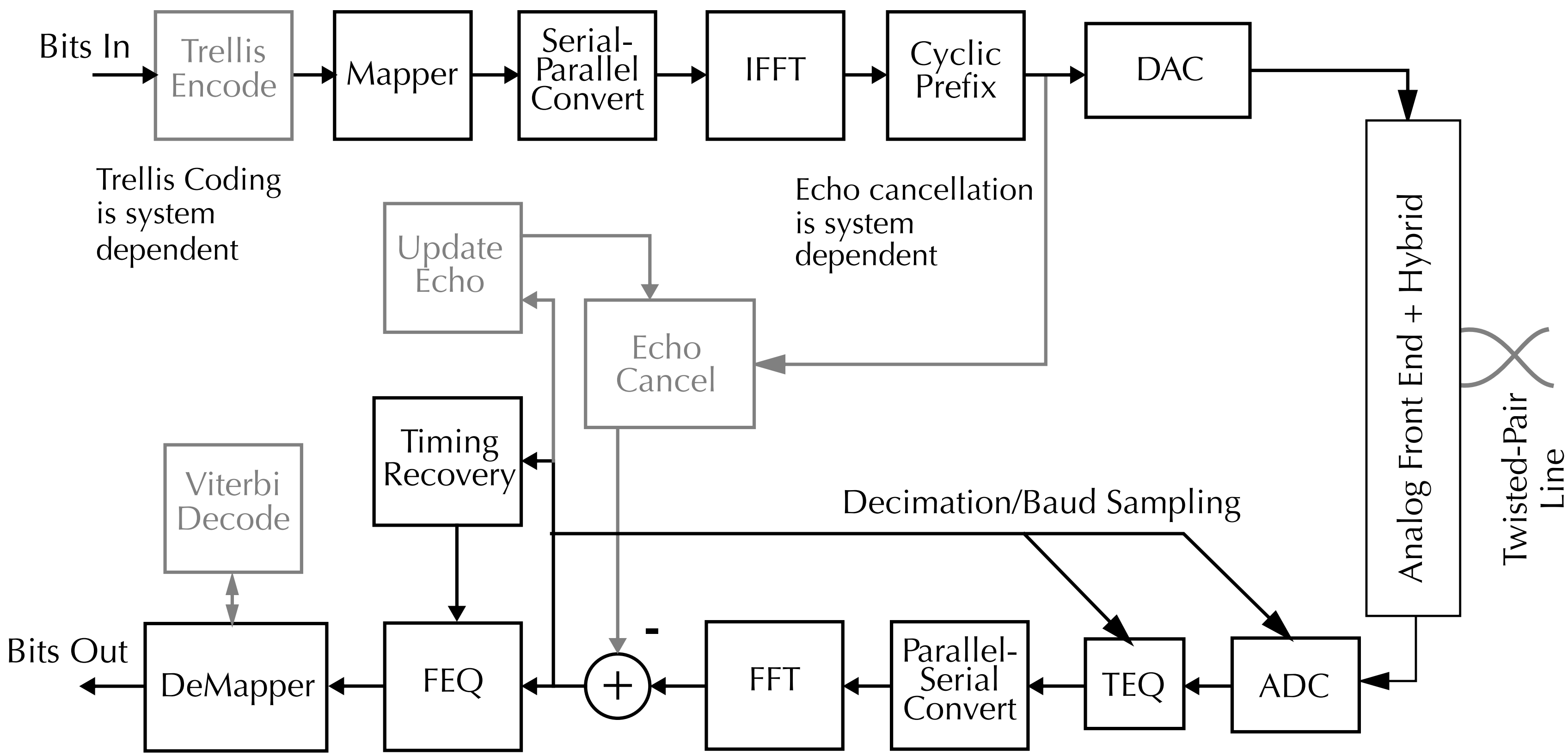
Without the splitter:

ADSL intermodulates into POTS band

POTS on/off hook affects ADSL signal

g.lite is "splitterless" for cost reasons (avoid rewiring).
Proving to be difficult to deploy; customer installed "microfilters" are required.

An ADSL Transceiver



- Processing Load ([Macq98])

  FFT/IFFT/TEQ: 70-90 MIPS (multiply-accumulate)

  Other DSP functions: 20-50 MIPS

  Total: 100-150 MIPS

ADSL: DSP vs. ASIC?

- DSP Approach
  - Extremely flexible, lower development costs
  - Time to market
  - Modem can evolve with standard via code change

- ASIC Approach
  - Reduced flexibility, longer development cycle
  - Power consumption: critical in central office

    200+ MHz DSP's vs. custom ASIC?

    "Low power" DSP techniques applicable in custom
  - Component may be cheaper (?)

- Both approaches seen in marketplace

ADSL: Analog Signal Processing Issues

- Goal of DMT: achieve as close to Shannon capacity as possible. Equivalently, maximize SNR in each bin

- Analog front-end performance (AFE) is critical

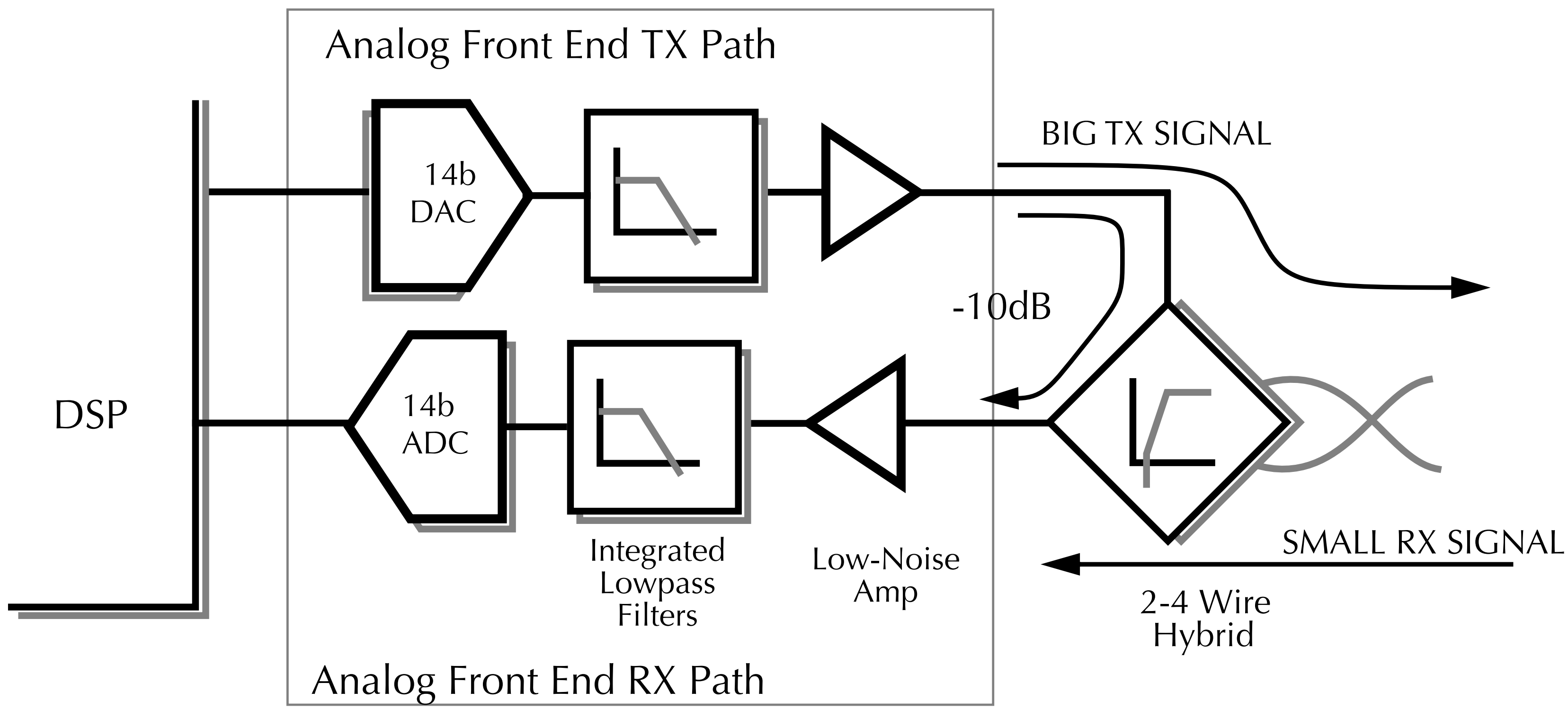
  Operating in frequencies of the line with tremendous attenuation

  Want AFE input referred noise significantly lower than line/crosstalk noise

  Intermodulation distortion in AFE will cause spillover from bin-to-bin: impacts noise floor

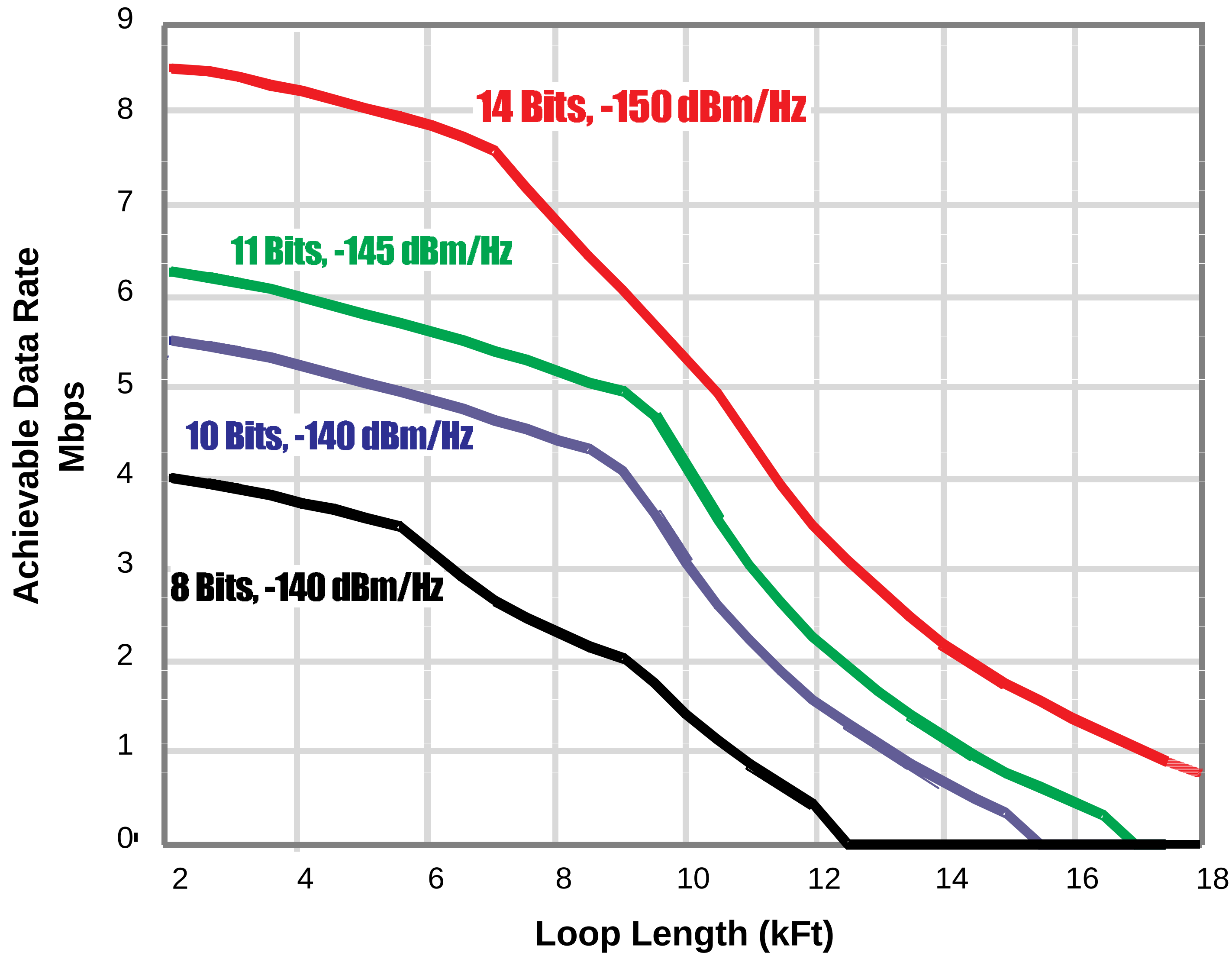
Analog front-end performance should not limit the system!

Dynamic Range Requirements in ADSL



- Key issue on longest lines: small in-band received signal along with huge out-of-band echo signal coming through the hybrid.
- Need 14-bit linear analog signal path (or better!) in the analog front end (AFE)

Impact of the AFE on ADSL System Performance



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A Few Words about SDSL...

- Symmetric (or Single-Pair) Digital Subscriber Line
  - Equal upstream/downstream data rates
  - Full duplex, single-pair
- Tends to be a single-pair variant of HDSL
- Early 1990's:
  - Marginally achieved 1.544 Mbps over 6 kft of 26 AWG wire
- Late 1990's:
  - *Wanted: symmetric system achieving 1.544 Mbps with the same reach and robustness as HDSL.*

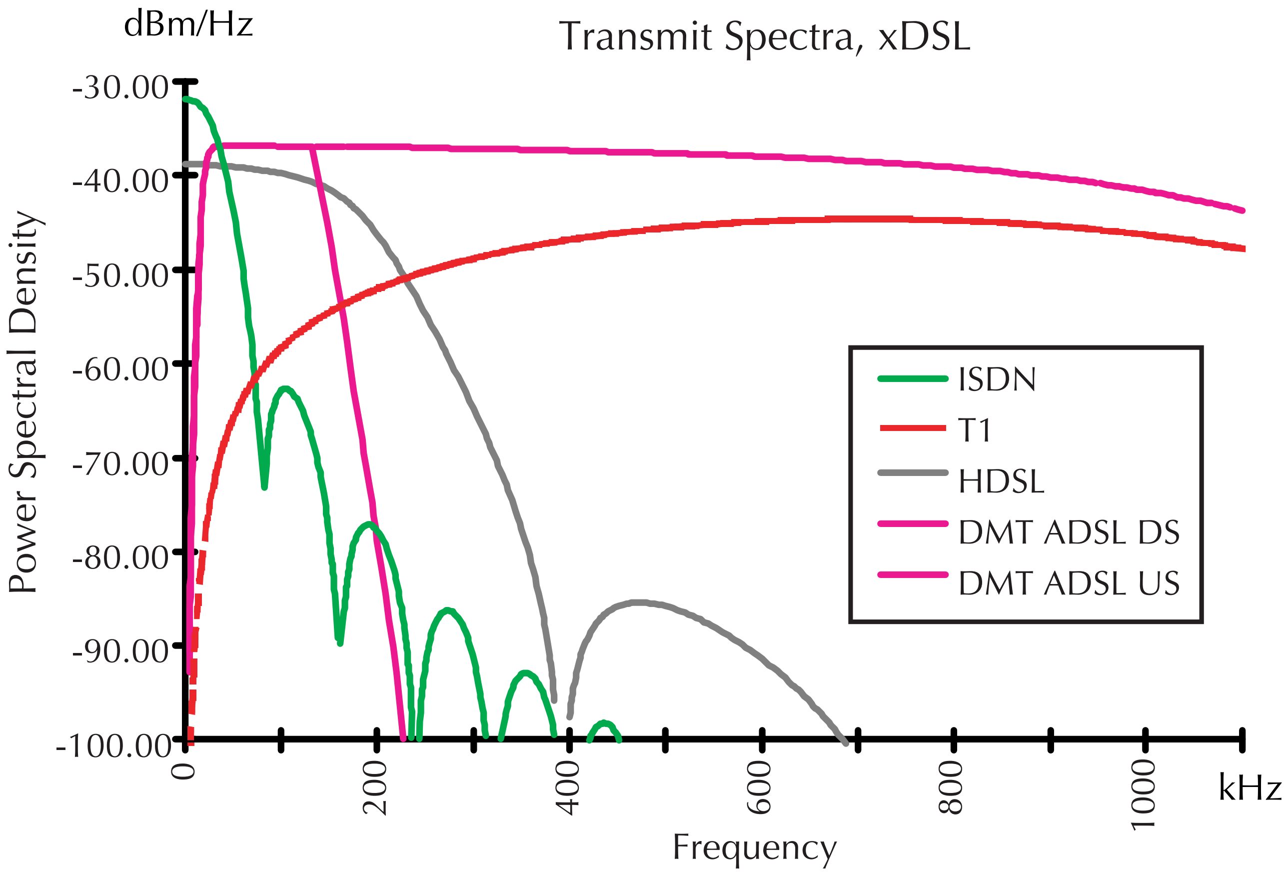
Utilization of advanced signal processing is key!

HDSL2

- Single-pair 1.544 Mbps transmission
  - 9000 ft. AWG 26, 12000 ft. AWG 24
  - Cannot adversely impact other xDSL systems present in binder
- Proposed Systems
  - Symmetric Echo-Cancelled Transmissions (SET)
  - Frequency-Division
  - *Partial Overlap Echo-Cancelled Transmission (POET)*
- End-to-end latency comparable to HDSL (< 500 usec)
- Still in committee; ratification likely later this year
- Modulation strategy:
  - 16-level PAM transmission with Trellis-Coding

HDSL2 Spectral Compatibility

- Critical issue: NEXT interaction in binder groups



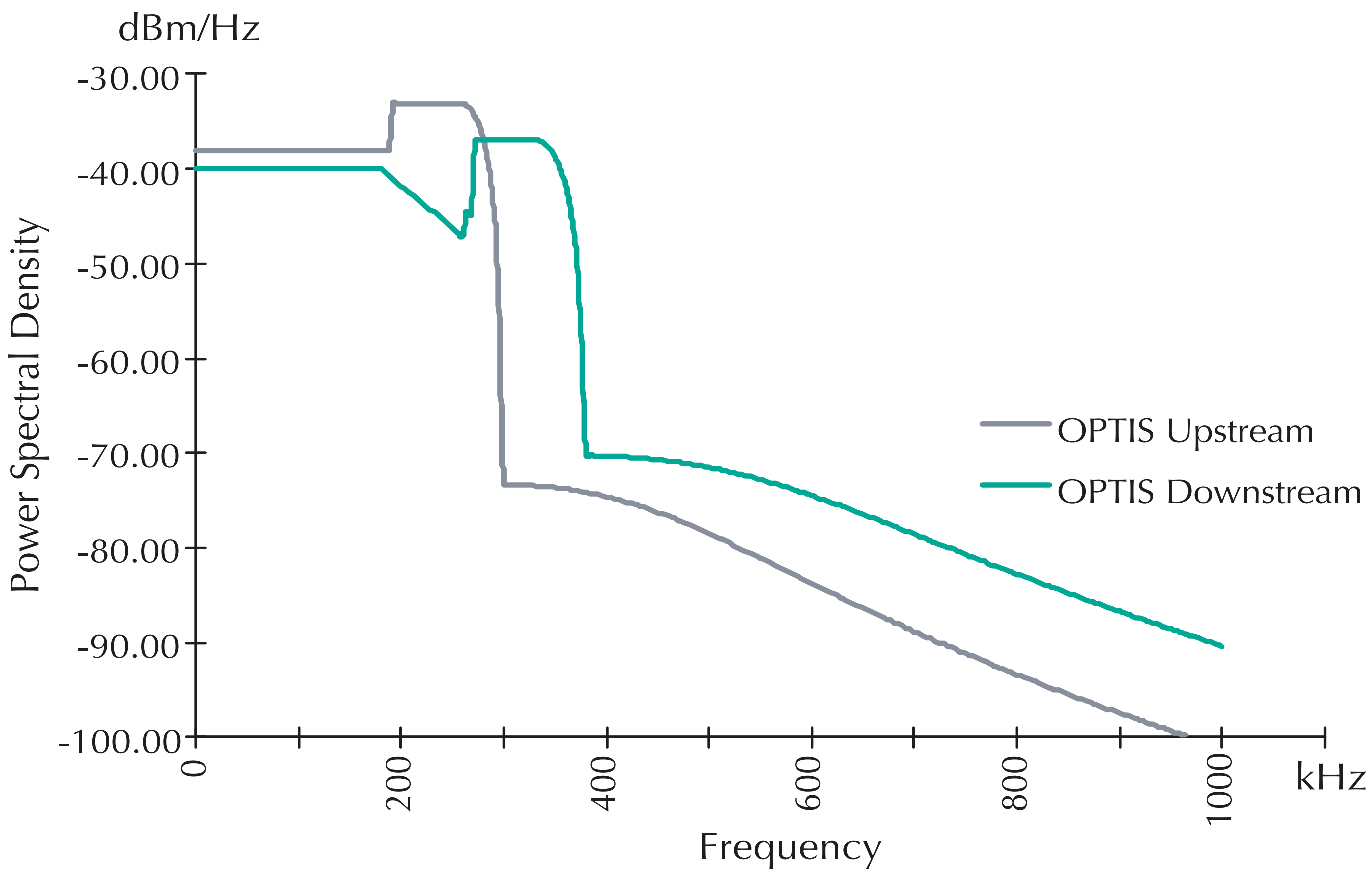
(figure cf. [Zimmer])

HDSL2: OPTIS Transmit Mask

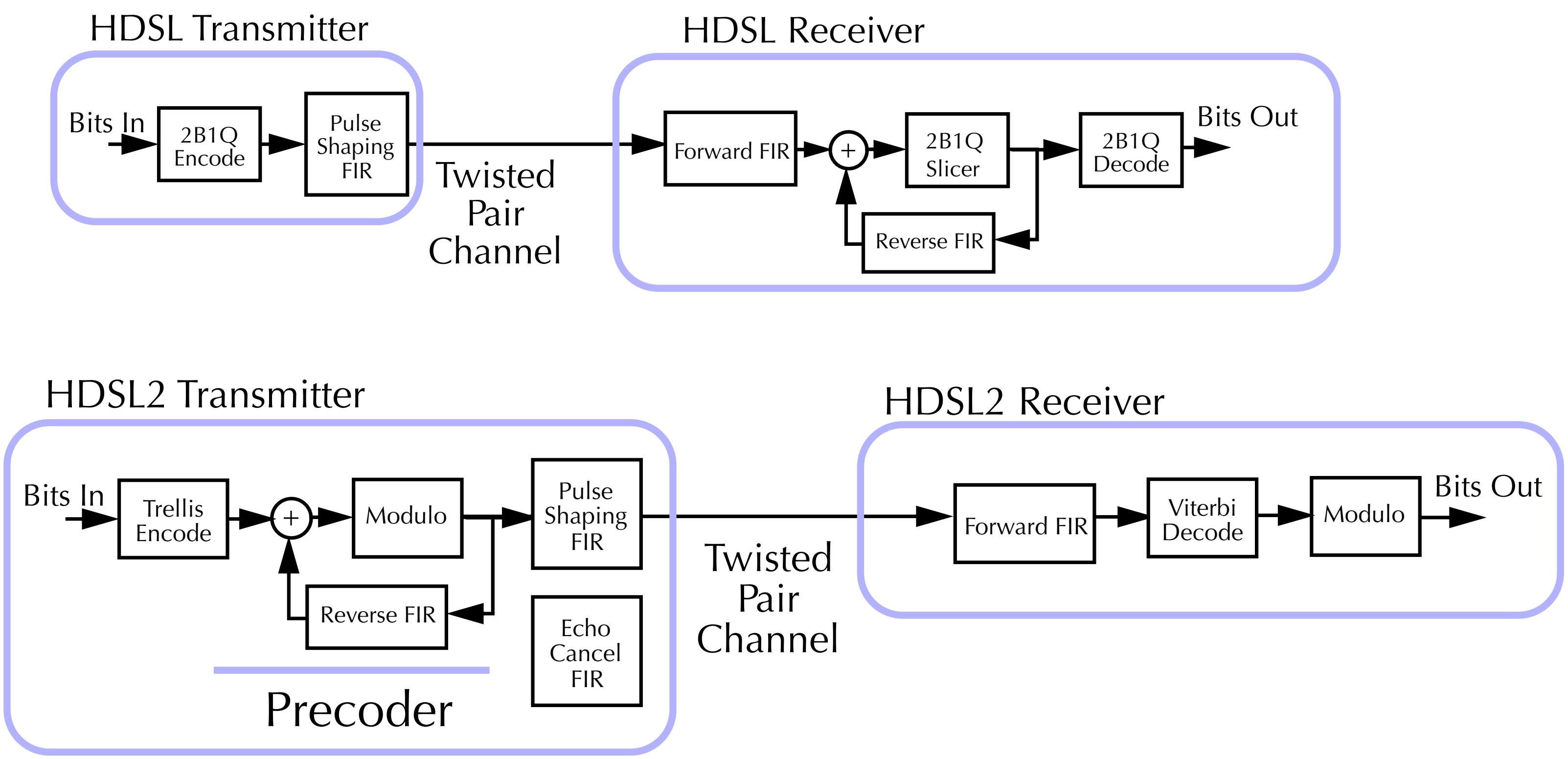
- Overlapped PAM Transmission with Interlocking Spectra

    Slightly asymmetric upstream/downstream spectrum

    Has superior spectral folding performance at baud sampling ([Zimmer])



HDSL2: Signal Processing Complexity I

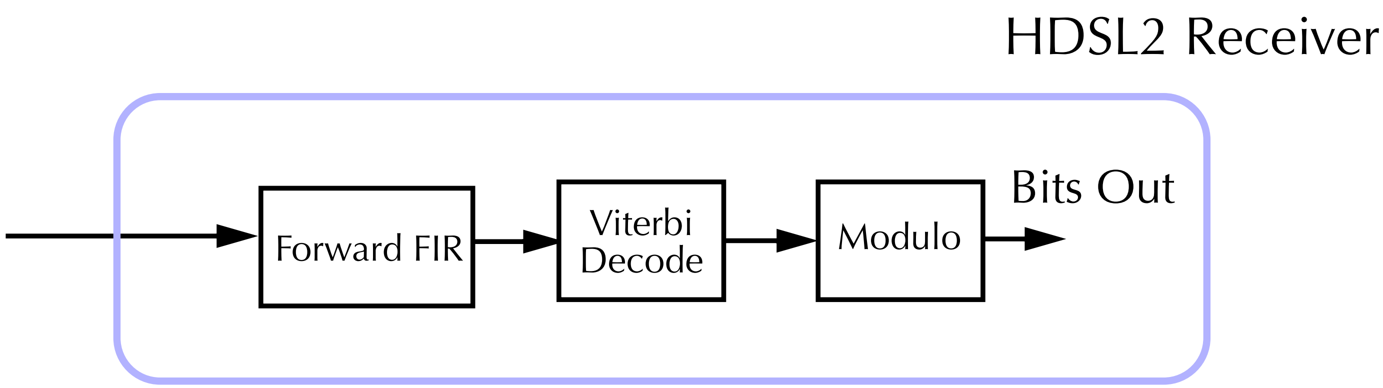


- Tomlinson-Harashima Precoding
  - Moves feedback equalizer in DFE into the transmitter
  - Eliminates DFE error propagation
  - Allows use of soft-decision error correction decoding
- Large complexity increase in transmitter (12-16 bits required)

HDSL2: Signal Processing Complexity II

- Use of Fractionally-Spaced Forward Equalizers

  Doubles complexity in receiver forward FIR



- Use of Trellis Coding

  Error Correction needs to provide > 4 dB (5.1 dB) SNR gain

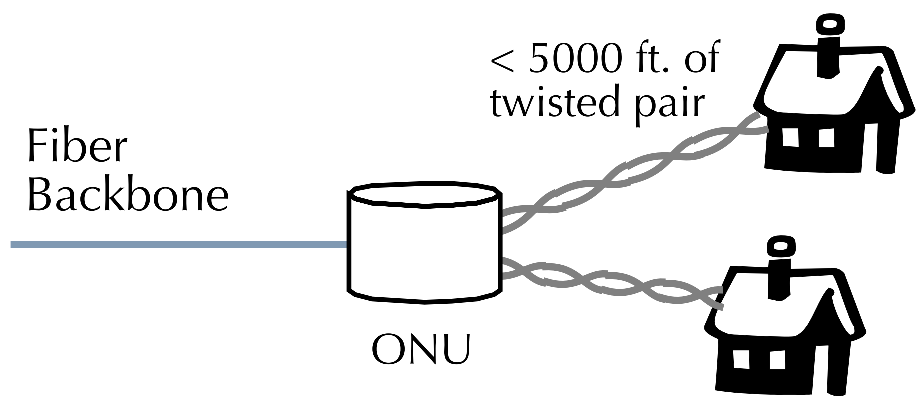
  Needs to be low latency

  32 to 512 state Viterbi detectors needed: HUGE complexity!

- Estimated Processing Requirements: 200-250 MIPS

Very High-Bit-Rate Digital Subscriber Line (VDSL)

- "Next generation" in data rate to customers:
  - Symmetric or nonsymmetric data services
  - 26 Mbps downstream, 3-26 Mbps upstream
  - Transmit bandwidth: ~ 3 - 20 MHz
- Short range: < 5000 ft. in loop
  - Depends having fiber-to-the-curb
  - Communicates to local ONU (optical network unit)



- Standard remains in question: DMT vs. QAM/CAP

VDSL: RF Ingress/Egress Issues

- RF Ingress

  AM Radio: Interference PSD on line~ -80 to -120 dBm/Hz

  0.56 - 1.6 MHz

  HAM Radio: Interference PSD on line ~ -35 to -80 dBm/Hz

  1.8 - 2.0 MHz
  3.5 - 4.0 MHz
  7.0 - 7.1 MHz
  10.1 - 10.15 MHz
  14.0 - 14.35 MHz
  ...

- VDSL Signals

  -60 dBm/Hz nominal transmit power spectrum

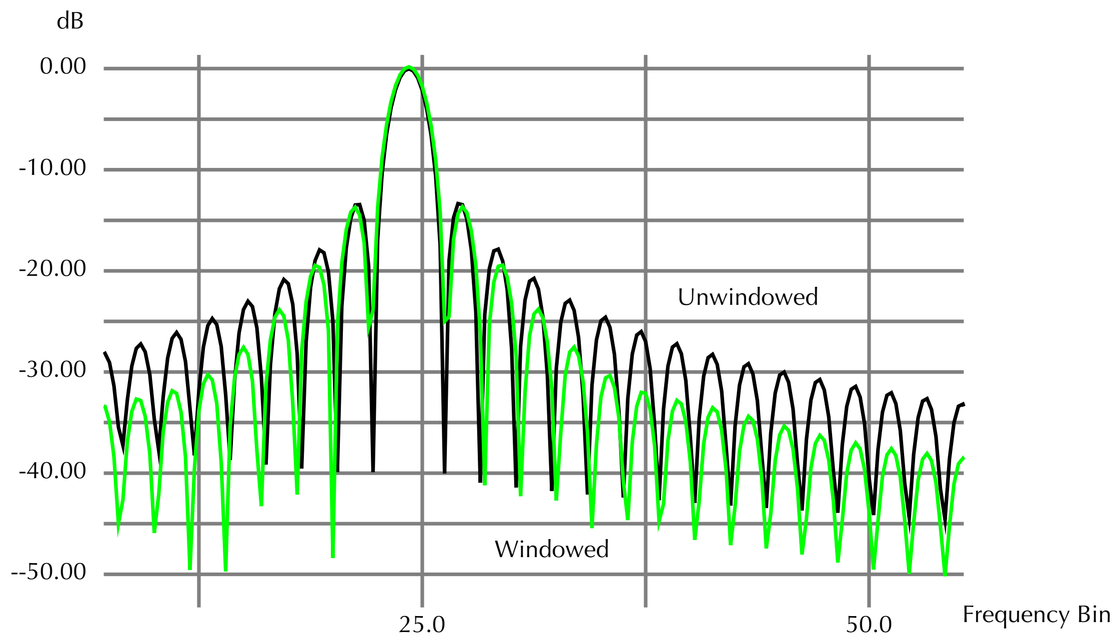
  Typical receive power spectrum (AWG 26, 2 kft)

  - 90 dBm/Hz @ 2 MHz
  - 140 dBm/Hz @ 10 MHz

RFI can be significantly larger than the received signal!

VDSL: RFI Cancellation (DMT systems)

- Problem: Sidelobes in FFT from RFI corrupt other bins



- Partial solution: Apply windowing before receiver FFT
- May lead to spectral broadening of received DMT tones

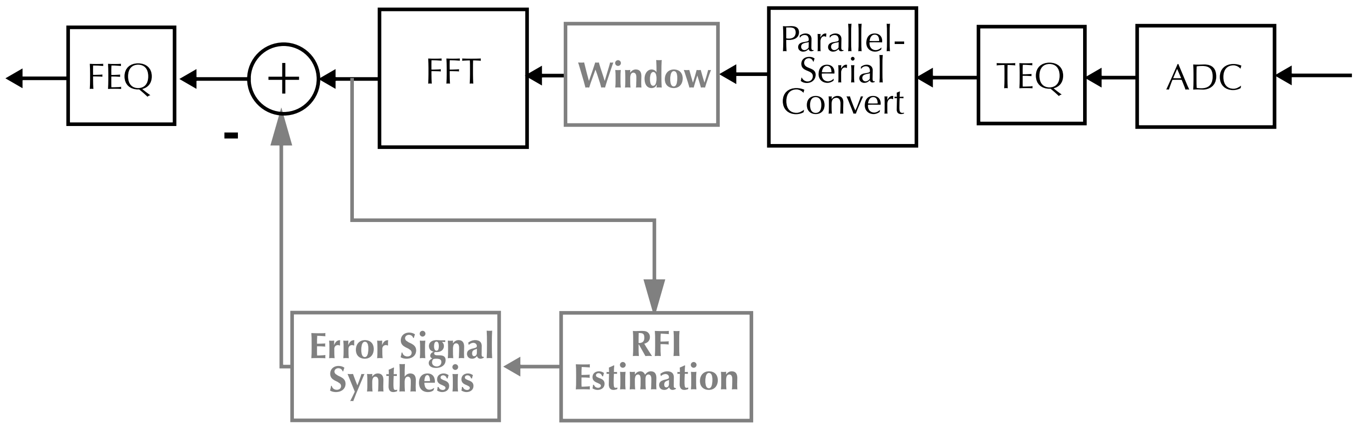
  Intersymbol interference in frequency domain (between bins)

  FEQ block now needs to consider ISI: decision feedback is needed

- Need to estimate and *eliminate* RFI interference

VDSL: RFI Cancellation (cont.)

- Modified DMT receiver



- Implementation Complexity

  Much higher sample rates

  Interference cancellation

  One recent VLSI solution [Alcatel99]:

  680k gates, 0.35u CMOS

  150 mm^2, 2.7W @ 3.3V

Conclusion

- xDSL has evolved on many fronts
  - Data rate
  - Reach
  - One pair vs. Two pair
- With each evolution, commensurate change in signal processing technology
  - HDSL: Adaptive DFE, echo cancellation
  - ADSL: DMT
  - VDSL: RFI cancellation, Very high-speed DSP
  - HDSL2: Tomlinson-Harashima precoding, Better error correction

Future xDSL's will continue this trend: leveraging signal processing toward higher speed and longer reach, over existing twisted pair installation!

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