EE 345S Real-Time Digital Signal Processing Lab Fall 2005

Data Conversion

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Some figures are from Ken C. Pohlmann, *Principles of Digital Audio*, McGraw-Hill, 1995.

Lecture 11

Solutions

- **Oversampling eases analog filter design**

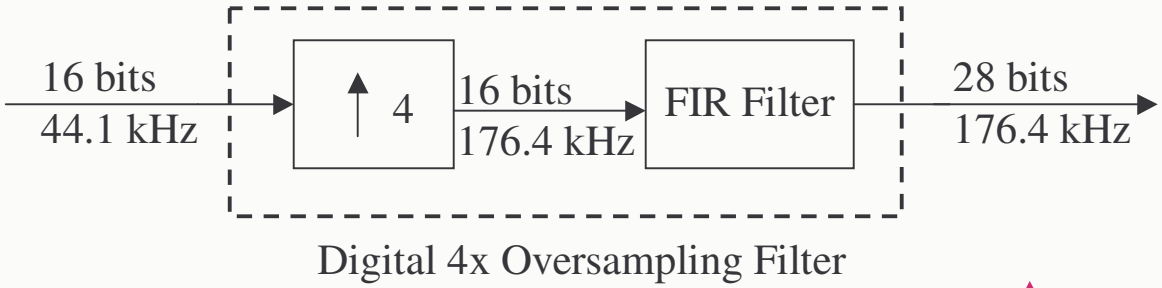
  Also creates spectrum to put noise at inaudible frequencies
- **Add dither (noise) at quantizer input**

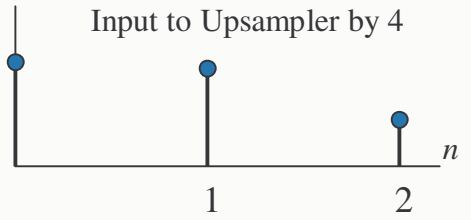
  Breaks up harmonics (idle tones) caused by quantization
- **Shape quantization noise into high frequencies**

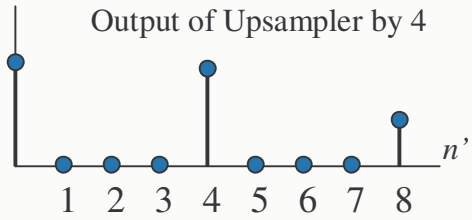
  Auditory system is less sensitive at higher frequencies
- **State-of-the-art in 20-bit/24-bit audio converters**

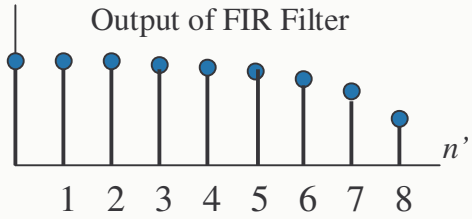
Oversampling	64x	256x	512x
Quantization	8 bits	6 bits	5 bits
Additive dither	2-bit Δ PDF	2-bit Δ PDF	2-bit Δ PDF
Noise shaping	5^{th} / 7^{th} order	5^{th} / 7^{th} order	5^{th} / 7^{th} order
Dynamic range	110 dB	120 dB	120 dB

Digital 4x Oversampling Filter



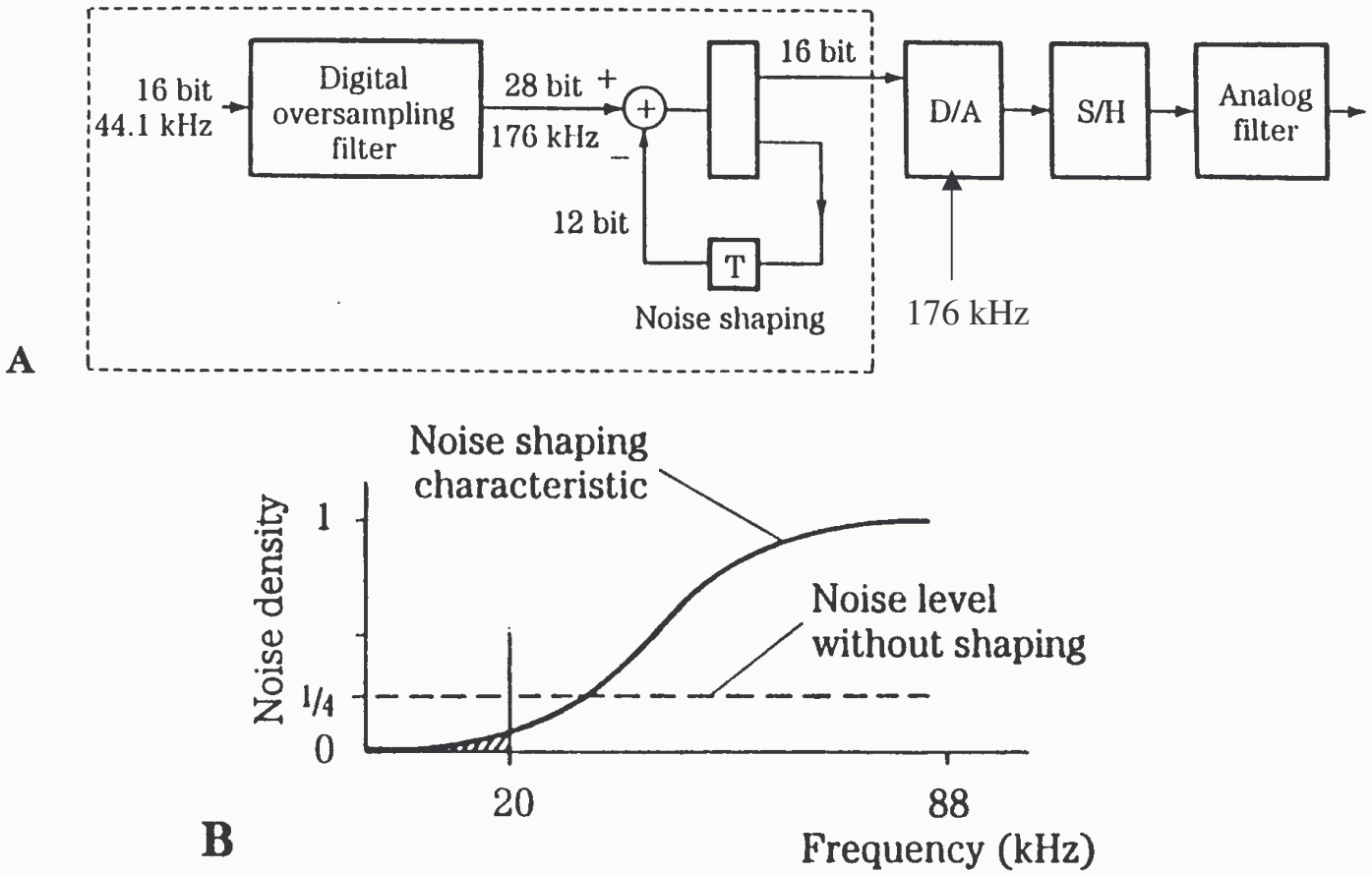






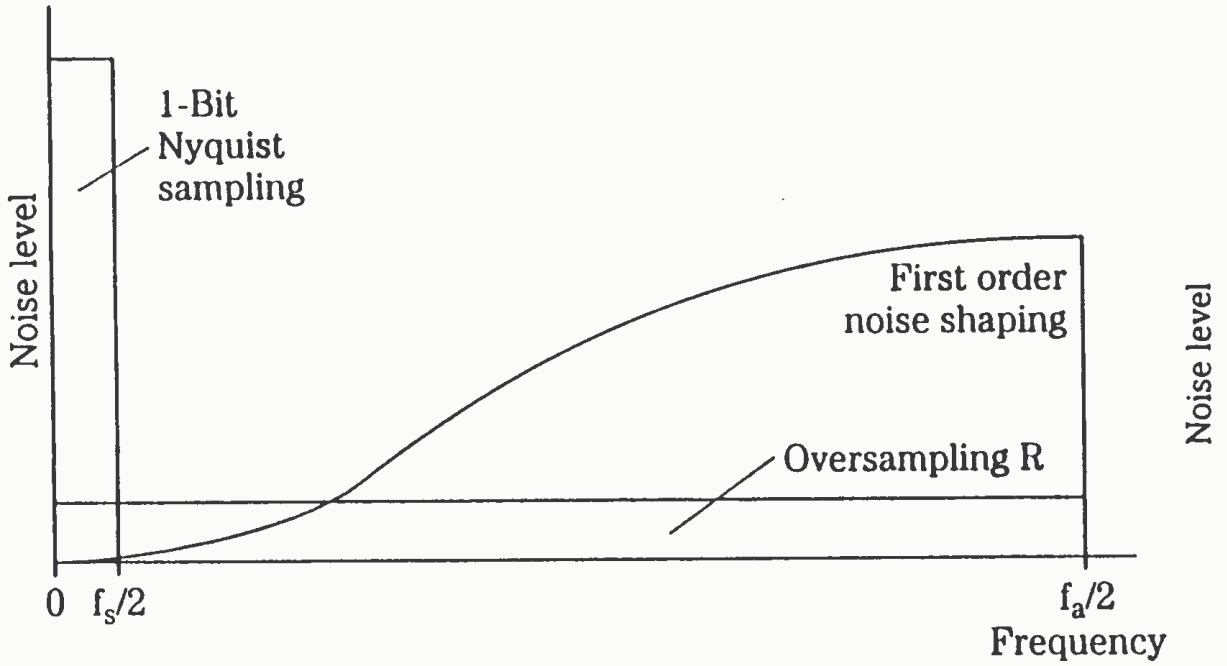
- **Upsampling by 4 (denoted by ↑4)**
  - For each input sample, output the input sample followed by three zeros
  - Four times the samples on output as input
  - Increases sampling rate by factor of 4
- **FIR filter performs interpolation**
  - Multiplying 16-bit data and 8-bit coefficient: 24-bit result
  - Adding two 24-bit numbers: 25-bit result
  - Adding 16 24-bit numbers: 28-bit result

Oversampling Plus Noise Shaping



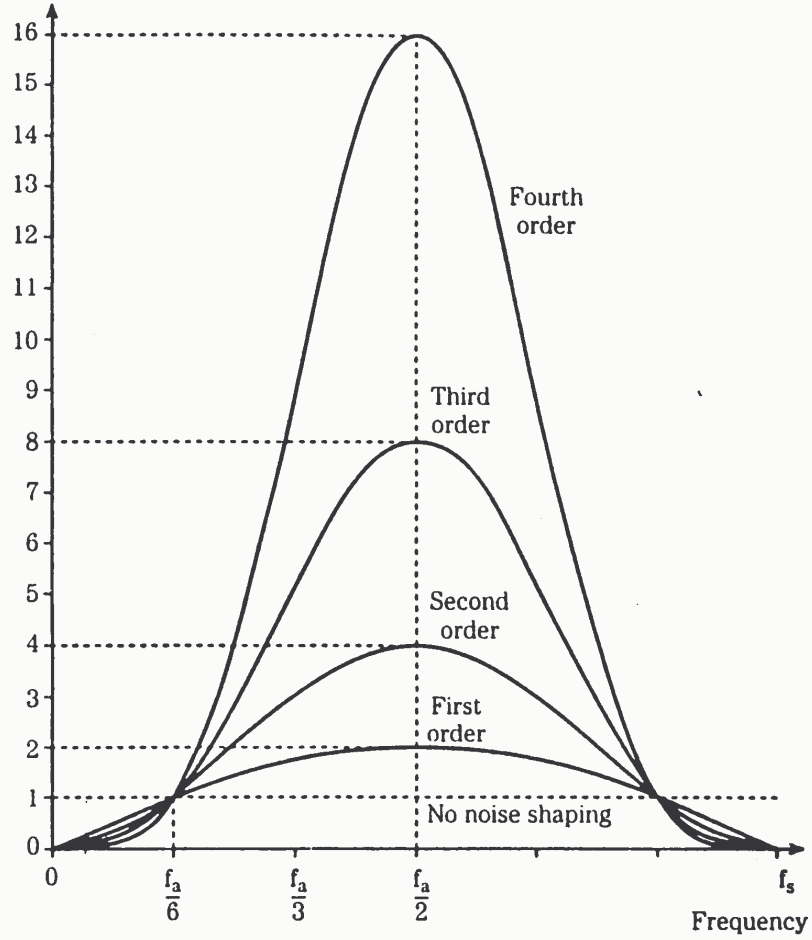
Pohlmann Fig. 4-17 Noise shaping following oversampling decreases in-band quantization error. A. Simple noise-shaping loop. B. Noise shaping suppresses noise in the audio band; boosted noise outside the audio band is filtered out.

Oversampling and Noise Shaping



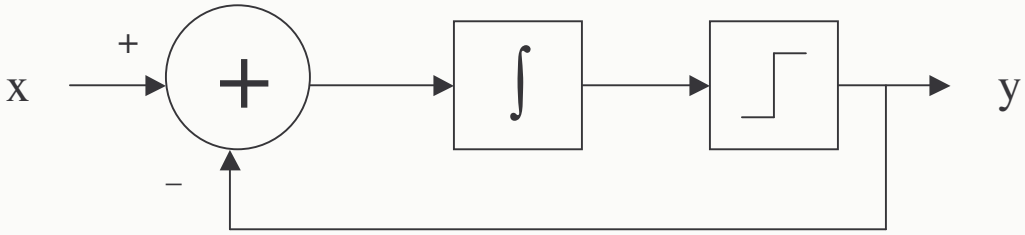
Pohlmann Fig. 16-4 With 1-bit conversion, quantization noise is quite high. In-band noise is reduced with oversampling. With noise shaping, quantization noise is shifted away from the audio band, further reducing in-band noise.

Oversampling and Noise Shaping



Pohlmann Fig. 16- 6 Higher orders of noise shaping result in more pronounced shifts in requantization noise.

First-Order Delta-Sigma Modulator

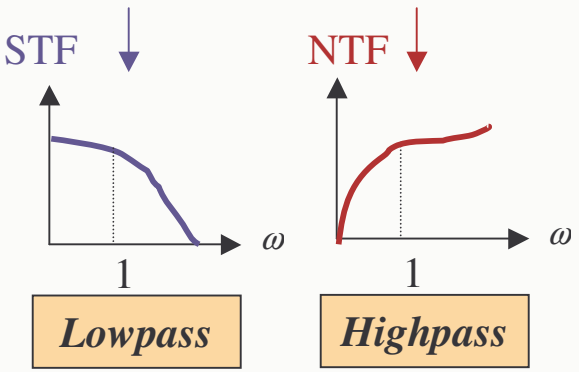


Assume quantizer adds uncorrelated white noise *n* *(model nonlinearity as additive noise)*

Continuous time: $\int = \frac{1}{s}$

$$Y(s) = \frac{X(s) - Y(s)}{s} + N(s)$$

$$Y(s) = \underbrace{\frac{1}{s+1}}_{\text{signal transfer function (STF)}} X(s) + \underbrace{\frac{s}{s+1}}_{\text{noise transfer function (NTF)}} N(s)$$



Discrete time: $\int = \frac{1}{1 - z^{-1}}$

$$Y(z) = (X(z) - Y(z)) \frac{1}{1 - z^{-1}} + N(z)$$

$$Y(z) = \underbrace{\frac{\frac{1}{2}}{1 - \frac{1}{2} z^{-1}}}_{\text{signal transfer function (STF)}} X(z) + \underbrace{\frac{1}{2} \frac{1 - z^{-1}}{1 - \frac{1}{2} z^{-1}}}_{\text{noise transfer function (NTF)}} N(z)$$

Lowpass ***Highpass***

Higher-order modulators

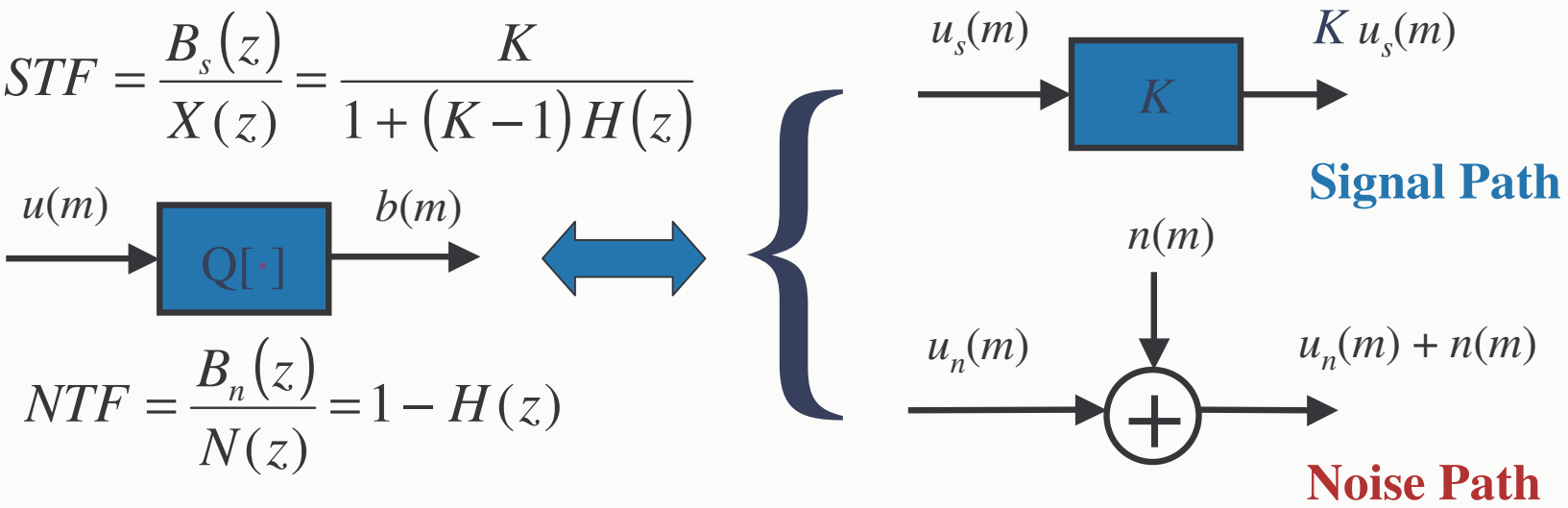
- Add more integrators
- Stability is a major issue

Noise-Shaped Feedback Coder

- **Type of sigma-delta modulator (see slide 9-6)**
- **Model quantizer as LTI** **[Ardalan & Paulos, 1988]**
  - Scales input signal by a gain by K (where $K > 1$)
  - Adds uncorrelated noise $n(m)$

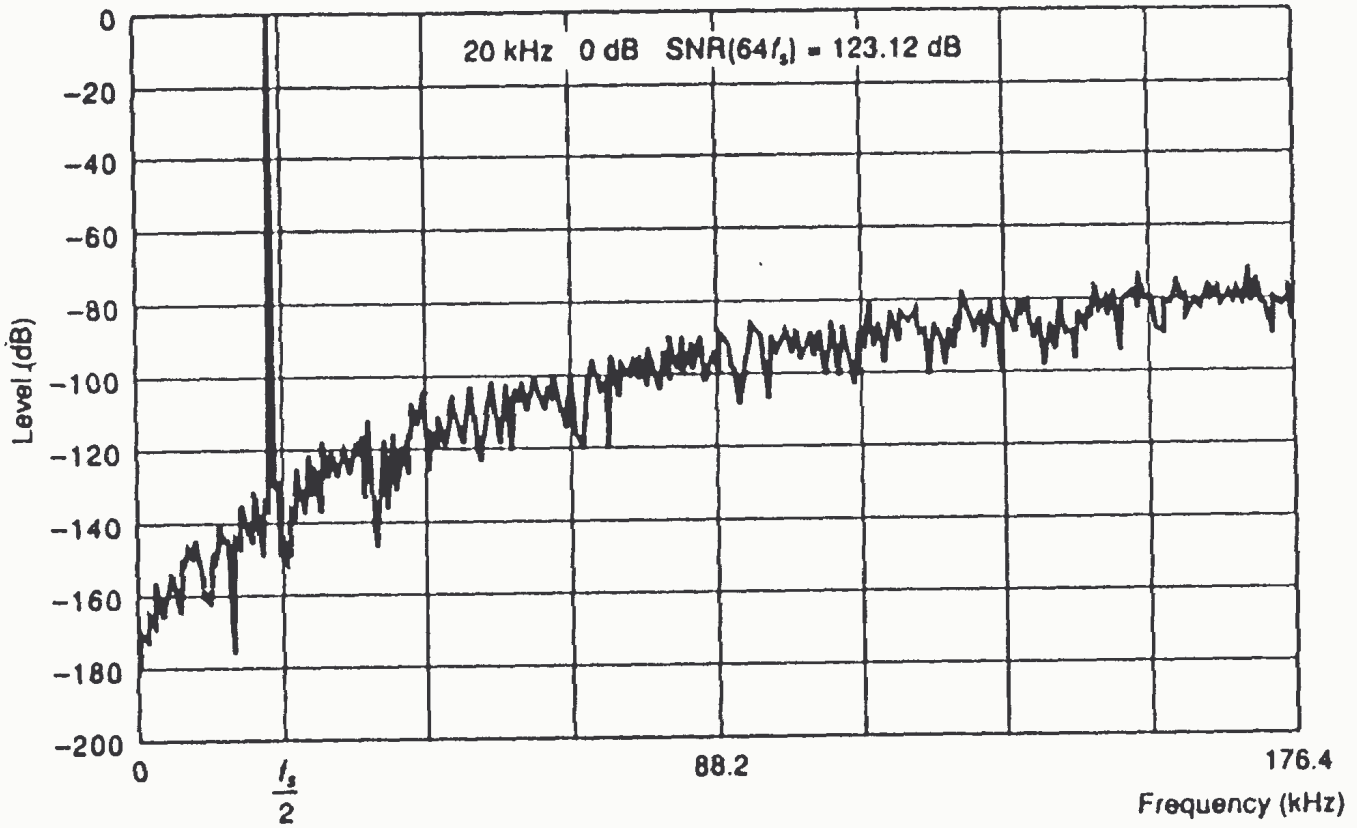
$$STF = \frac{B_s(z)}{X(z)} = \frac{K}{1+(K-1)H(z)}$$

$$NTF = \frac{B_n(z)}{N(z)} = 1 - H(z)$$



NTF is highpass $\Rightarrow$ H(z) is lowpass $\Rightarrow$ STF passes low frequencies and amplifies high frequencies

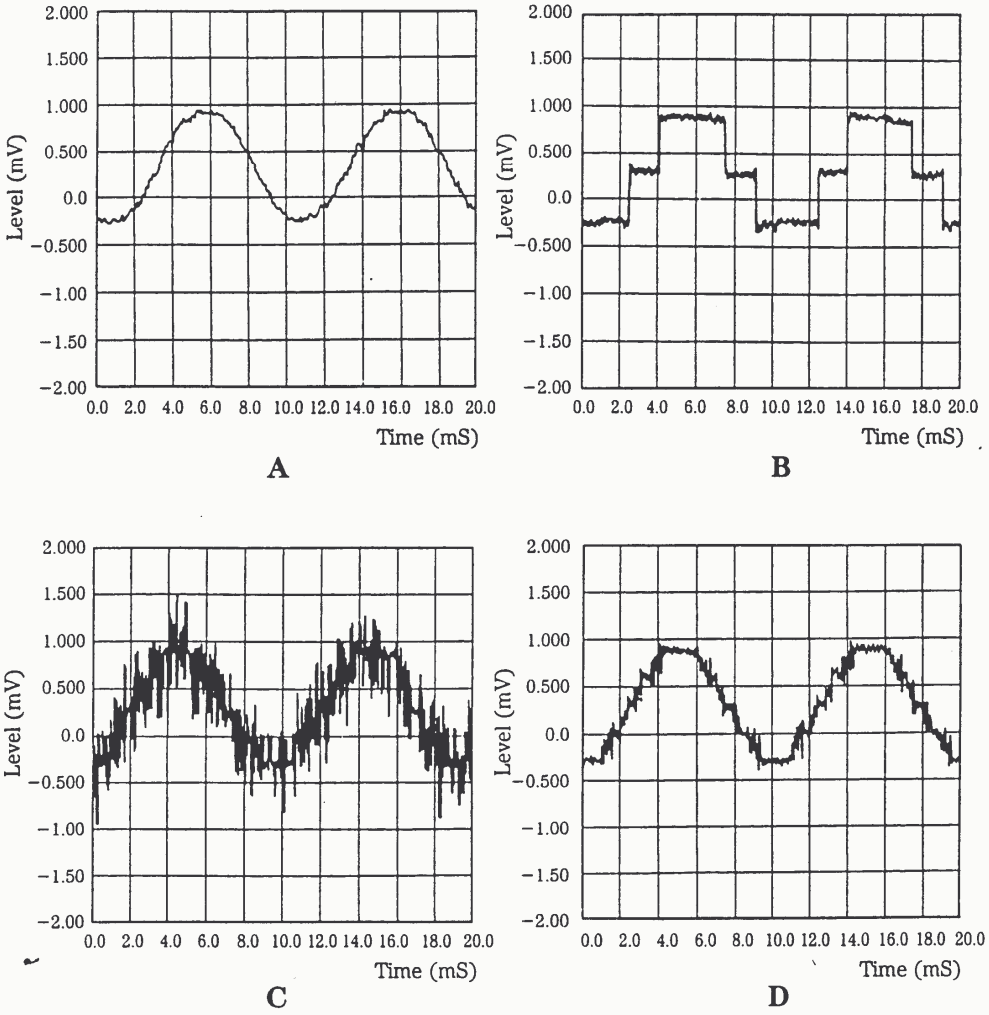
Third-order Noise Shaper Results



Pohlmann Fig. 16-13 Reproduction of a 20 kHz waveform showing the effect of third-order noise shaping. Matsushita Electric

19-Bit Resolution from a CD: Part I

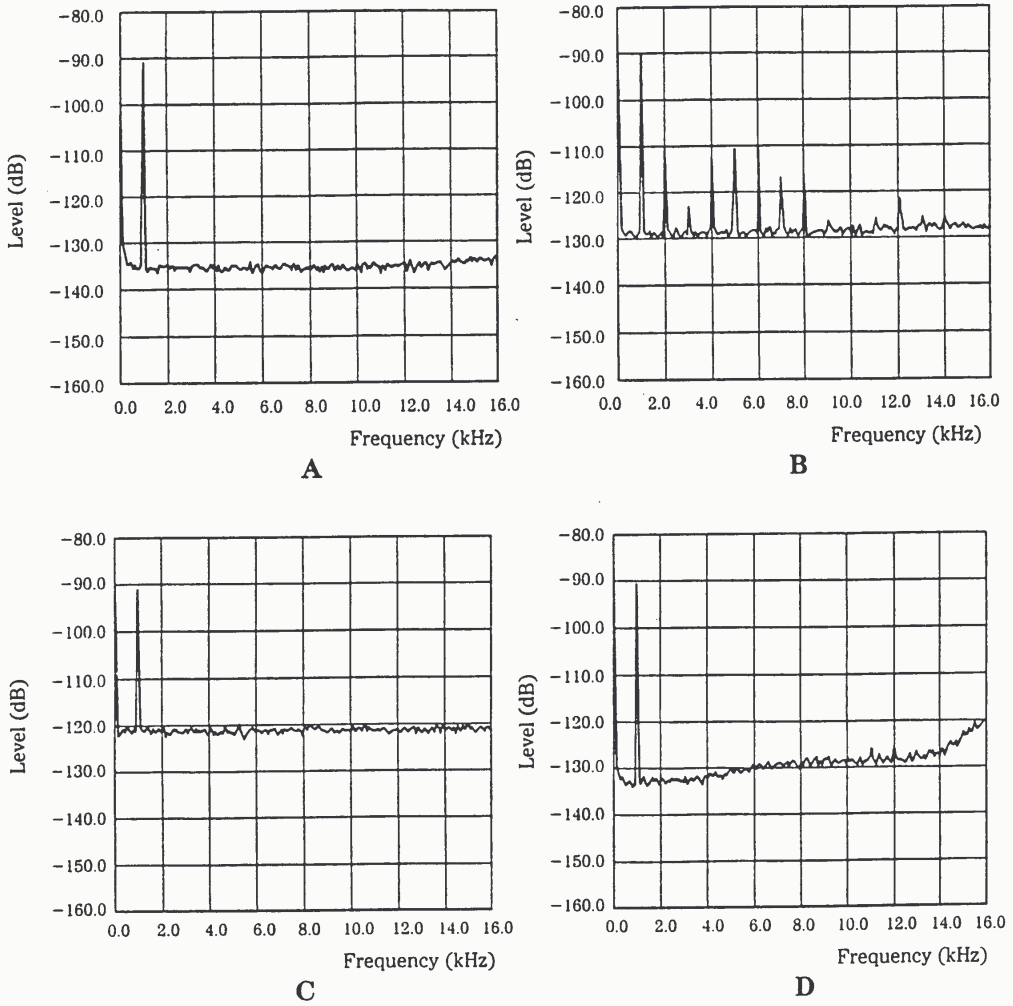
Poh1man Fig. 6-27 An example of noise shaping showing a 1 kHz sinewave with -90 dB amplitude; measurements are made with a 16 kHz lowpass filter.
A. Original 20 bit recording.
B. Truncated 16 bit signal.
C. Dithered 16 bit signal.
D. Noise shaping preserves information in lower 4 bits.



19-Bit Resolution from a CD: Part II

Pohlmann Fig. 16-28 An example of noise shaping showing the spectrum of a 1 kHz, -90 dB sinewave (from Fig. 16-27).
A. Original 20-bit recording
B. Truncated 16-bit signal
C. Dithered 16-bit signal
D. Noise shaping reduces low and medium frequency noise.

Sony's Super Bit Mapping uses psycho-acoustic noise shaping (instead of sigma-delta modulation) to convert studio masters recorded at 20-24 bits/sample into CD audio at 16 bits/sample. All Dire Straits albums are available in this format.



Open Issues in Audio CD Converters

- **Oversampling systems used in 44.1 kHz converters**
  - Digital anti-imaging filters (anti-aliasing filters in the case of A/D converters) can be improved (from paper by J. Dunn)
- ***Ripple*: Near-sinusoidal ripple of passband can be interpreted as due to sum of original signal and smaller pre- and post-echoes of original signal**
  - Ripple magnitude and no. of cycles in passband correspond to echoes up to 0.8 ms either side of direct signal and between -120 and -50 dB in amplitude relative to direct
  - Post-echo masked by signal, but pre-echo is not masked
  - Solution is to reduce passband ripple. Human hearing is no better than 0.1 dB at its most sensitive, but associated pre-echo from 0.1 dB passband ripple is audible.

Open Issues in Audio CD Converters

- ***Stopband rejection* (A/D Converter)**
  - Anti-aliasing filters are often half-band type with only 6 dB attenuation at 1/2 of sampling rate.
  - Do not adequately reject frequencies that will alias.
  - Ideal filter rolls off at 20 kHz and attenuates below the noise floor by 22.05 kHz, but many converter designs do not achieve this
- ***Stopband rejection* (D/A Converter)**
  - Same as for A/D converters
  - Additional problem: intermodulation products in passband. Signal from the D/A converter fed to a (power) amplifier which may have nonlinearity, especially at high frequencies where the open loop gain is falling.

Audio-Only DVDs

- **Sampling rate of 96 kHz with resolution of 24 bits**
  - Dynamic range of 6.02 B + 1.17 = 145.17 dB
  - Marketing ploy to get people to buy more disks
- **Cannot provide better performance than CD**
  - Hearing limited to 20 kHz: sampling rates > 40 kHz wasted
  - Dynamic range in typical living room is 70 dB SPL
    - **Noise floor 40 dB Sound Pressure Level (SPL)**
    - **Most loudspeakers will not produce even 110 dB SPL**
  - Dynamic range in a quiet room less than 80 dB SPL
  - No audio A/D or D/A converter has true 24-bit performance
- **Why not release a tiny DVD with the same capacity as a CD, with CD format audio on it?**

Super Audio CD (SACD) Format

- **One-bit digital audio bitstream**
  - Being promoted by Sony and Philips (CD patents expired)
  - SACD player uses a green laser (rather than CD's infrared)
  - Dual-layer format for play on an ordinary CD player
- **Direct Stream Digital (DSD) bitstream**
  - Produced by 1-bit 5th-order sigma-delta converter operating at 2.8224 MHz (oversampling ratio of 64 vs. CD sampling)
  - Problems with 1-bit converters: distortion, noise modulation, and high out-of-band noise power.
- **Problems with 1-bit stream (S. Lipshitz, AES 2000)**
  - Cannot properly add dither without overloading quantizer
  - Suffers from distortion, noise modulation, and idle tones

AC-3 Audio Format

- **5.1 channel format**
  - 5 full-spectrum channels (left, right, front, and two surround channels)
  - Subwoofer channel that is limited to 200 Hz
- **Compressed to 384 kbps**
  - Transmission
  - Storage between the sprocket holes of 35 mm film in the case of Dolby Digital

Conclusion on Audio Formats

- **Audio CD format**
  - Fine as a delivery format
  - Converters have some room for improvement
- **Audio DVD format**
  - Not justified from audio perspective
  - Appears to be a marketing ploy
- **Super Audio CD format**
  - Good specifications on paper
  - Not needed: conventional audio CD is more than adequate
  - 1-bit quantization cannot be made to work correctly
  - Another marketing ploy (17-year patents expiring)