1 Quiz 2 (qz2)

2 Why digital?

Discussion: What is to be gained from digital audio?

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3 Some definitions

- Signal: 
- Analog signal: 
- Digital signal: 
- Binary signal: 
- Noise: 
- Distortion: 
- Harmonic distortion: 
- Inharmonic distortion:
4 Analog-digital conversion

Two-step process, usually (but not necessarily!) performed in order of:
1. Sampling
2. Quantization

5 Sampling

5.1 Sampling theorem

- As long as we comply with the sampling theorem, we can restore the original signal without loss of information or quality.
  - Unless we also quantize (which, in practice, an ADC always does)
  - But no information loss inherent to (correctly performed) sampling!

- Interpreting the sampling theorem from two different angles:
To faithfully reconstruct a sampled signal whose maximum frequency is $f_{\text{max}}$, we must choose a sample rate $f_S > 2 \cdot f_{\text{max}}$.

For a given sample rate $f_S$, the Nyquist frequency $f_N = \frac{f_S}{2}$ represents the highest frequency that can be faithfully reproduced.

**How does reconstruction of original signal come about?**

- Sampled signal’s spectrum = copies of original spectrum centered around multiples of $f_S$
- Reconstruction filter (LP tuned to $f_{\text{max}}$) discards upper sidebands

**Reconstruction filter = last stage of DAC (but here quantization has occurred, too)!**

### 5.2 Aliasing (undersampling)

- Result of sampling theorem violation, i.e., when $f_{\text{max}} > \frac{f_S}{2}$
- Sidebands overlap and HF components from upper sidebands are ‘folded back’ down into audible spectrum
- Audible as inharmonic distortion
- Visual analogy: backward-turning wheel in movies
• How to prevent aliasing?
  – *Anti-aliasing filter* (LP tuned to \( f_N \)) before sampling
  – Same kind of filter as reconstruction filter, but different purpose

5.3 Signal reconstruction & oversampling

5.4 Jitter

• Deliberate use of higher sample rate than sampling theorem demands
• Allows the use of (cheaper) reconstruction filters with a less steep slope
• Redistributes quantization noise beyond audible range\(^1\)

\( f \)

\[ -2 \cdot f_S \quad -f_S \quad -\frac{f_S}{2} \quad \frac{f_S}{2} \quad f_S \quad 2 \cdot f_S \]

\[ \cdots \]

\[ \text{Correctly sampled} \]

\[ \text{Oversampled} \]

\[ \text{Less steep filter} \]

\[ \cdots \]

\[ f \]

Figure 6. Deliberate oversampling allows the use of less steep reconstruction filters (after Lyons 2004, fig. 2.4)

\[ f \]

\[ \cdots \]

\[ -f_S \quad -\frac{f_S}{2} \quad 0 \quad \frac{f_S}{2} \quad f_S \]

\[ \text{Less steep filter} \]

\[ \cdots \]

\[ f \]

Figure 7. Playing back a digital signal on a jittering sample clock results in distortion.

• *A\( d\)c and *d\( a\)c are driven by sample clock* (quartz crystal oscillator)
• *Jitter* is an irregularity of that sample clock\(^2\)

\(^1\) Cf., Bohn 1997, p. 8.

\(^2\) Cf., Katz 2014b
• Causes distortion when audio recorded on a sample clock with jitter is played back on a sample-clock without jitter (or vice versa)
• See Katz \cite{Katz2014} for detailed discussion of jitter

6 Quantization
6.1 Binary numbers
• Digit … decimal (0 or 1 or 2 or … or 9)
• Bit … binary digit (0 or 1)
• Binary-to-decimal conversion:
  \[ 1001_2 = 1 \cdot 2^3 + 0 \cdot 2^2 + 0 \cdot 2^1 + 1 \cdot 2^0 = 8 + 0 + 0 + 1 = 9 \]
• Same principle as: \( 975_{10} = 9 \cdot 10^2 + 7 \cdot 10^1 + 5 \cdot 10^0 \)

6.2 Bit depth
• Can express \( 10^N \) numeric values with \( N \) digits (base-10 number system)
• Can express \( 2^N \) numeric values with \( N \) bits (base-2 number system)
• E.g., \( 2^{16} = 65536 \) possible amplitude values with 16bit

6.3 Quantizing error
• Difference between original and quantized signal
• Audible as:
  – Background noise for high-level signals
  – Distortion for low-level signals (where error correlates with signal)
• Determines available dynamic range
\[ \Delta L_{\text{dig}} \approx (6 \cdot N) \text{ dB} \]

6.4 Dither\(^3\)
• Weird: we deliberately add noise to make things sound better \( \odot \)
• Trade off distortion from quantizing error against background noise
• Reason: Background noise perceptually less annoying than distortion
• Effectively linearizes transfer function
• Goal: Extend perceived dynamic range downwards
• Different types of dither:\(^4\)
  – Rectangular pdf

\[ \begin{array}{c}
\text{Figure 8. Quantizing error } E_Q \text{ of a 3 bit ADC} \\
\end{array} \]

\(^3\) Montgomery \cite{Montgomery2012} discusses dither in an engaging video. Together with another video by Montgomery \cite{Montgomery2010}, this provides an excellent in-depth introduction to digital audio for especially interested students.

\(^4\) Cf., Watkinson \cite{Watkinson2001} pp. 231 ff.
- Triangular pdf
- Gaussian pdf

• Noise shaping filters dithering noise to be less intrusive.

• Dither and noise-shaping options in Reaper: File >> Render...

• Rules of ᵇ:
  - Dither when moving from high to lower bitrate (often 24 to 16)⁵
  - Dither only once, as the very last step!⁶

7 Preview: Ed4 assignment

References & further reading


