Nyquist-Rate D/A Converters

D/A Converter Basics.

\[ B_{in} \rightarrow \text{D/A} \rightarrow V_{out} \]

- \( B_{in} \) is a digital signal (or word),
  \[ B_{in} = b_1 2^{-1} + b_2 2^{-2} + \ldots + b_N 2^{-N} \]  \( \text{(1)} \)
- \( b_i \) equals a “1” or a “0” (i.e. a binary digit).
- \( V_{ref} \) — an analog reference; \( V_{out} \) — output.
  \[ V_{out} = V_{ref}(b_1 2^{-1} + b_2 2^{-2} + \ldots + b_N 2^{-N}) \]  \( \text{(2)} \)
- Define \( V_{LSB} \) to be LSB signal change, \( V_{LSB} \equiv \frac{V_{ref}}{2^N} \)
**D/A Converter Basics**

- For errors, define “units” of LSB $1\ 	ext{LSB} = \frac{1}{2^N}$
- A *multiplying* D/A allows $V_{\text{ref}}$ to be a *varying input* — $V_{\text{out}}$ proportional to multiplication of $V_{\text{ref}}$ and $B_{\text{in}}$.
- For *ideal* D/A, output signal is a *well defined value* — no quantization error!

\[
\frac{V_{\text{out}}}{V_{\text{ref}}} = \frac{1}{4} = 1\ \text{LSB}
\]

**D/A Resistor-String**

- Guaranteed monotonic
- Integrated with better than 10-bits absolute accuracy.
- Delay through the switch network major speed limitation
- Resistors might be realized using polysilicon
- If n-channel only used, can be laid out small
- Requires $2^N$ resistors
D/A Resistor-String — Digital Decoding

- Higher speed implementation (less resistance thru transistors)
- Large cap load on buffer input
- Can pipeline digital decoding for faster speed
- Requires $2^N$ resistors

Folded-resistor-string D/A

- Less capacitance load over the single bus approach
- Requires $2^N$ resistors
Binary-Weighted Resistor D/A’s.

\[ V_{out} = -R_F V_{ref} \left( -\frac{b_1}{2R} - \frac{b_2}{4R} - \frac{b_3}{8R} - \ldots \right) \]  (3)

- Only N resistors
- Resistor and current ratios are on the order of \(2^N\)
- No guarantee of monotonicity.
- Prone to glitches (more later).

Reduced Spread Binary Resistor D/A

\[ V_A = \frac{1}{4} (-V_{ref}) \]

- Reduced resistor spread
- Keep repeating this procedure \(\rightarrow\) R-2R ladder
**R-2R Based D/A Converters**

- Small size, good matching (only R and 2R)

\[
\begin{align*}
R_1 & \quad R'_1 \\
R_2 & \quad R'_2 \\
R_3 & \quad R'_3 \\
R_4 & \quad R'_4 \\
\end{align*}
\]

\[
V_{ref} \quad 2R \quad 2R \quad 2R \quad 2R \quad 2R
\]

\[
\frac{V_{ref}}{2R} \quad \frac{V_{ref}}{4R} \quad \frac{V_{ref}}{8R} \quad \frac{V_{ref}}{16R}
\]

- \( R'_4 = 2R \)
- \( R_4 = 2R \parallel 2R = R \)
- \( R'_3 = R + R_4 = 2R \)
- \( R_3 = 2R \parallel R'_3 = R \)

**R-2R Based Resistor Ladders**

- Example D/A converter

- Currents through the switches are scaled
- Should scale switch sizes for good accuracy
- No node voltage changes except for output \( \rightarrow \) fast
R-2R Based Resistor Ladders

- Slower circuit having equal current through switches

![Resistor Ladder Diagram]

- Node voltages change — slower circuit
- No need to scale switch sizes (smaller size)

Glitches

- Different delays for switching the different currents
- MSB change often worst case

- Glitches can be minimized by limiting the bandwidth but that slows down circuit
- Use thermometer code to reduce glitches
Charge-Redistribution SC D/A’s

- Programmable SC gain amplifier.
- Sign bit realized by interchanging input phases
- Carefully clock-waveforms required to minimize voltage dependency of clock-feed-through.
- Digital codes should be changed when input side of capacitors are connected to ground. Requires extra digital complexity.

Thermometer D/A Converters

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<th>Decimal</th>
<th>Binary</th>
<th>Thermometer Code</th>
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</tbody>
</table>

Binary-to-thermometer code conversion

$V_{out}$
**Thermometer Code D/A Converter**

- Top Capacitors are Connected to Ground
- Bottom Capacitors are Connected to $V_{ref}$
- $2^N$ unit sized caps
- Guaranteed monotonic
- Much lower glitching
- Low DNL

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**Current-Mode D/A’s**

- Thermometer-code
- High-speed, output feeds directly to resistor
  - Important that delay to all the switches are equal.
- Overlapped clocks much better than having non-overlapped clocks.
Segmented D/A

- Combine thermometer and binary
- Accuracy needed for LSB reduced
- Glitches reduced
- Very popular

Vref

2R 2R 2R 2R

R/2

Vout

• Combine thermometer and binary
• Accuracy needed for LSB reduced
• Glitches reduced
• Very popular