EECS 247

Analog-Digital Interface
Integrated Circuits

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Instructor: Haideh Khorramabadi

UCB
Department of Electrical Engineering and
Computer Sciences

Administrative

• Course web page:
  http://www.eecs.berkeley.edu/~EE247
  – All handouts are available on the web

• Office hours for Haideh Khorramabadi
  – Tuesday 2-4pm @ 463 Cory Hall
  – Email: haidehk@eecs.berkeley.edu

• Homework is posted on the course website and are due on
  Thursdays

• Midterm 10/19
Analog-Digital Interface Circuits

• Naturally occurring signals are analog
  ⇒ Need Analog/Digital & Digital/Analog interface circuits

Question: Why not process the signal with analog circuits only & thus eliminate need for A/D & D/A?

MOSFET Maximum $f_t$ v.s. Time

Ref: Paul R. Gray UCB EE290 course 95
Digital Signal Processing Characteristics

• Direct benefit from the down scaling of VLSI technology
• Not sensitive to “analog” noise
• Enhanced functionality & flexibility
• Amenable to automated design & test
• “Arbitrary” precision
• Provides inexpensive storage capability

Analog Signal Processing Characteristics

• Has not fully benefited from the down scaling of VLSI technology
  – Supply voltages scale down accordingly
    → reduced voltage swings
  – Reduced voltage swings requires lowering of the circuit noise to keep a constant dynamic range
    → Higher power dissipation and chip area
• Sensitive to “analog” noise
• Not amenable to automated design
• Extra precision comes at a high price
• Availability of inexpensive digital capabilities on-chip enables automatic adjustments to compensate for analog circuit impairments
• Rapid progress in DSP has imposed higher demands on analog/digital interface circuitry
  → Plenty of room for innovations!
Cost/Function Comparison
DSP & Analog

- Digital circuitry: Fully benefited from CMOS device scaling
  - Cost/function decreases by ~29% each year
    \[ \rightarrow \text{Cost/function 30X in 10 years} \]

- Analog circuitry: Not fully benefited from CMOS scaling
  - Device scaling mandates drop in supply voltages→ threaten analog feasibility
    \[ \rightarrow \text{Cost/function for analog ckt almost constant or increase} \]

- Rapid shift of functions from analog to digital signal processing & hence need for A/D & D/A interface circuitry


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Example: Digital Audio

- Goal-Lossless archival and transmission of audio signals
- Circuit functions:
  - Preprocessing
    - Amplification
    - Anti-alias filtering
  - A/D Conversion
    - Resolution\(\rightarrow\)16Bits
    - Sig. bandwidth\(\rightarrow\)41kHz
  - DSP
    - Storage
    - Processing (e.g. recognition)
  - D/A Conversion
  - Postprocessing
    - Smoothing filter
    - Amplification

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Example: Typical Cell Phone

Contains in integrated form:

- 4 Rx filters
- 4 Tx filters
- 4 Rx ADCs
- 4 Tx DACs
- 3 Auxiliary ADCs
- 8 Auxiliary DACs

Dual Standard, I/Q

Audio, Tx/Rx power control, Battery charge control, display, ...

Total: Filters $\rightarrow$ 8
ADCs $\rightarrow$ 7
DACs $\rightarrow$ 12

Areas Utilizing Analog/Digital Interface Circuitry

- Communications
  - Wireline communications
    - Telephone related (DSL, ISDN, CODEC)
    - Television circuitry (Cable modems, TV tuners...)
    - Ethernet (Gigabit, 10/100BaseT...)
  - Wireless
    - Cellular telephone (CDMA, Analog, GSM....)
    - Wireless LAN (Blue tooth, 802.11a/b/g....)
    - Radio (analog & digital), Television

- Computing & Control
  - Storage media (disk drives, digital tape)
  - Imagers & displays

- Instrumentation
  - Test equipment
  - Physical sensors & actuators

- Consumer Electronics
  - Audio (CD, DAT)
  - Automotive control, appliances, toys
UCB Analog Courses
EECS 247 - 240 - 242

- EECS 247
  - Filters, ADCs, DACs, some system level
  - Signal processing fundamentals
  - Macro-models, large systems, some transistor level, constraints such as finite gain,
    supply voltage, noise, dynamic range considered
  - CAD Tools → Matlab, SPICE

- EECS 240
  - Transistor level, building blocks such as opamps, buffers, comparator,…
  - Device and circuit fundamentals
  - CAD Tools → SPICE

- EECS 242
  - RF amplification, mixing
  - Oscillators
  - Exotic technology devices
  - Nonlinear circuits

Material Covered in EE247

- Filters
  - Continuous -time filters
    - Biquads & ladder type filters
    - Opamp-RC, Opamp-MOSFET-C, gm-C filters
    - Automatic frequency tuning
  - Switched capacitor (SC) filters

- Data Converters
  - D/A converter architectures
  - A/D converter
    - Nyquist rate ADC- Flash, Pipeline ADCs,…
    - Oversampled converters
    - Self-calibration techniques

- Systems utilizing analog/digital interfaces
  - Wireline communication systems- ISDN, XDSL…
  - Wireless communication systems- Wireless LAN, Cellular telephone,…
  - Disk drive electronics
  - Fiber-optics systems
Introduction to Filters

- Filtering → Frequency-selective signal processing
  - It’s the most common type of signal processing
  - Examples:
    • Extraction of desired signal from many (radio)
    • Separating signal and noise
    • Amplifier bandwidth limitations

\[ |H(j\omega)| \]

Ideal Low-Pass Brick Wall Filter

\[ |H(j\omega)| \]

More Practical Filter

Simplest Filter
First-Order RC Filter (LPF1)

Steady-state frequency response:

\[
H(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{1}{1 + \frac{s}{\omega_c}}
\]

with \( \omega_c = \frac{1}{RC} = 2\pi \times 100kHz \)
Poles and Zeros

$$H(s) = \frac{1}{1 + \frac{s}{\omega_0}}$$

Pole: \( p = -\omega_0 \)

Zero: \( z \to \infty \)

Filter Frequency Response

Bode Plot

- 20 dB/dec magnitude rolloff
- 90 degrees phase shift per 2 decades

Question: can we really get 100dB attenuation at 10GHz?
First-Order RC Filter Including Parasitics (LPF2)

\[ H(s) = \frac{1 + sRC_p}{1 + sR(C + C_p)} \]

Pole: \( p = -\frac{1}{R(C + C_p)} \approx -\frac{1}{RC} \)

Zero: \( z = -\frac{1}{RC_p} \)

Filter Frequency Response

\[ |H(j\omega)|_{\omega=0} = 1 \]

\[ |H(j\omega)|_{\omega\to\infty} = \frac{C_p}{C + C_p} \]

\[ \approx \frac{C_p}{C} \]

\[ = 10^{-3} \]

\[ = -60dB \]

• Beware of other parasitics not included in this model …
Dynamic Range & Electronic Noise

- Dynamic range is defined as the ratio of maximum possible signal handled by a circuit to the minimum useful signal
  - Maximum signal handling capability usually limited by circuit non-linearity & maximum possible voltage swings which in turn is a function of supply voltage
  - Minimum signal handling capability is normally determined by electronic noise
    - Amplifier noise due to device thermal and flicker noise
    - Resistor thermal noise
- Dynamic range in analog circuits has direct implications for power dissipation

Analog Dynamic Range

- Once the poles and zeroes of the analog filter transfer function are defined then special attention must be paid to the actual implementation

- Of the infinitely many ways to build a filter with a given transfer function, each of those ways has a different output noise!

- As an example noise and dynamic range for the 1st order lowpass filter will be derived
First Order Filter Noise

- Capacitors are noiseless
- Resistors have thermal noise
  - This noise is uniformly distributed from dc to infinity
  - Frequency-independent noise is called “white noise”

Resistor Noise

- Resistor noise characteristics
  - A mean value of zero
  - A mean-squared value

\[ \overline{v^2} = 4k_b T R \Delta f \]

Boltzmann’s constant = 1.38e-23 J/°K
Resistor Noise

- Resistor rms noise voltage in a 10Hz band centered at 1kHz is the same as resistor rms noise in a 10Hz band centered at 1GHz

- Resistor noise spectral density, $N_0$, is the rms noise per $\sqrt{\text{Hz}}$ of bandwidth:

$$N_0 = \sqrt{\frac{V^2}{\Delta f}} = \sqrt{4k_BT/R}$$

Resistor Noise

Good numbers to memorize:

- $N_0$ for a $1k\Omega$ resistor at room temperature is $4nV/\sqrt{\text{Hz}}$

- Scaling $R$,
  - A $10M\Omega$ resistor gives $400nV/\sqrt{\text{Hz}}$
  - A $50\Omega$ resistor gives $0.9nV/\sqrt{\text{Hz}}$

- Or, remember

  $$k_BT = 4 \times 10^{-21} \text{ J} \quad (T_r = 17 \degree \text{C})$$

- Or, remember

  $$k_BT/q = 26 \text{ mV} \quad (q = 1.6 \times 10^{-19} \text{ C})$$
First Order Filter Noise

- Short circuit the input to ground.
- Resistor noise gives the filter a non-zero output when $v_{IN}=0$
- In this simple example, both the input signal and the resistor noise obviously have the same transfer functions to the output.
- Since noise has random phase, we can use any polarity convention for a noise source (but we have to use it consistently).

First Order Filter Noise

- What is the thermal noise of the RC filter?
- Let's ask SPICE!

Netlist:

```plaintext
*Noise from RC LPF
vin vin 0 ac 1V
r1 vin vout 8kOhm
c1 vout 0 1nF
.ac dec 100 10Hz 1GHz
.noise V(vout) vin
.end
```
Total Noise

- Total noise is what the display on a volt-meter connected to \( v_o \) would show!
- Total noise is found by integrating the noise power spectral density within the frequency band of interest.
- Note that noise is integrated in the mean-squared domain, because noise in a bandwidth \( df \) around frequency \( f_1 \) is uncorrelated with noise in a bandwidth \( df \) around frequency \( f_2 \).
  - Powers of uncorrelated random variables add.
  - Squared transfer functions appear in the mean-squared integral:

\[
\overline{v_o^2} = \int_0^\infty 4k_BT R|H(2\pi f f)|^2 df
\]
Total Noise

\[ \overline{v_n^2} = \int_{0}^{\infty} 4kT R \left( \frac{1}{2\pi f R C} \right) df + \int_{0}^{\infty} 4kT R \left( \frac{i}{1 + 2\pi f j R C} \right) df = \frac{kT}{C} \]

- This interesting and somewhat counter intuitive result means that even though resistors provide the noise sources, total noise is determined by noiseless capacitors!

- For a given capacitance, as resistance goes up, the increase in noise density is balanced by a decrease in noise bandwidth

kT/C Noise

- kT/C noise is a fundamental analog circuit limitation

- The rms noise voltage of the simplest possible (first order) filter is \( \sqrt{kT/C} \)

- For 1pF capacitor, \( \sqrt{kT/C} = 64 \mu V\)-rms (at 298°K)

- 1000pF gives 2 \( \mu V\)-rms

- The noise of a more complex & higher order filter is given by:
  \[ \sqrt{\alpha \times kT/C} \]

  where \( \alpha \) depends on implementation and features such as filter order
LPF1 Output Noise

- Note that the integrated noise essentially stops growing above 100kHz for this 20kHz lowpass filter

- Beware of faulty intuition which might tempt you to believe that an 80Ω, 1000pF filter has lower integrated noise compared to our 8000Ω, 1000pF filter…
Analog Circuit Dynamic Range

- Maximum voltage swing for analog circuits can at most be equal to power supply voltage $V_{DD}$ (normally is smaller)
- Assuming a sinusoid signal
  $$V_{\text{rms}}(\text{rms}) = \frac{1}{\sqrt{2}} \frac{V_{\text{pp}}}{2}$$
- Noise for a filter:
  $$V_n(\text{rms}) = \sqrt{\frac{kT}{C}}$$
  $$DR = \frac{V_{\text{max}}(\text{rms})}{V_n(\text{rms})} = \frac{V_{DD}\sqrt{C}}{8\pi kT}$$  [V/V]
  - Dynamic range in dB is:
    $$= 20\log_{10}\left(\frac{V_{DD}\sqrt{C}}{V_n}\right) + 75$$  [dB] with C in [pF]
**Analog Circuit Dynamic Range**

- For integrated circuits built in modern CMOS processes, $V_{DD} < 3\text{V}$ and $C < 100\text{pF}$ ($\alpha = 1$)
  - $\text{DR} < 104\text{dB}$

- For PC board circuits built with “old-fashioned” 30V opamps and discrete capacitors of $< 100\text{nF}$
  - $\text{DR} < 140\text{dB}$
  - A 36dB advantage!

**Dynamic Range versus Bits**

- Bits and dB are related:
  \[
  DR = 1.76 + 6.02N \quad [\text{dB}]
  \]
  - see “quantization noise”, later in the course

- Hence
  
  \[
  \begin{align*}
  104 \text{ dB} & \rightarrow 17 \text{ Bits} \\
  140 \text{ dB} & \rightarrow 23 \text{ Bits}
  \end{align*}
  \]
Dynamic Range versus Power Dissipation

- Each extra bit corresponds to 6dB
- 6dB means cutting noise power by 4!
- This translates into 4x larger capacitors
- To drive these at the same speed, $G_m$ must increase 4x
- Power is proportional to $G_m$ (for fixed supply and $V_{dsat}$)

In analog circuits with performance limited by thermal noise, 1 extra bit costs 4x power
E.g. 16Bit ADC at 200mW $\rightarrow$ 17Bit ADC at 800mW

Do not overdesign the dynamic range of analog circuits!

Noise Summary

- Thermal noise is a fundamental property of (electronic) circuits
- Noise is closely related to
  - Capacitor size
- In higher order filters, noise is proportional to $C$, filter order, $Q$, and depends on implementation
- Operational amplifiers can contribute significantly to overall filter noise
- Reducing noise in most analog circuits costs in terms of power dissipation and chip area