EECS 247

Analog-Digital Interface
Integrated Circuits

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Administrative

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

• Office hours for Haideh Khorramabadi
  – Tues./Thurs. 3-4pm @ 485 Cory Hall
  – Email: haidehk@eecs.berkeley.edu

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

• Midterm exam: 10/20/05
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 $f_t$ versus 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
    \[\text{Cost/function decreases by } 30\times \text{in 10 years}\]
- Analog circuitry: Not fully benefited from CMOS scaling
  - Device scaling mandates drop in supply voltages
    - Threaten analog feasibility
      \[\text{Cost/function for analog ckt almost constant or increase}\]
- 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
    - Variable gain amplification

\[\text{Analog Input} \downarrow \text{Analog Preprocessing} \downarrow \text{A/D Conversion} \downarrow \text{DSP} \downarrow \text{D/A Conversion} \downarrow \text{Analog Postprocessing} \downarrow \text{Analog Output}\]
Example: Typical Dual Mode 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 → 8
ADCs → 7
DACs → 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

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

\[ \omega_b \]

Ideal Low-Pass Brick Wall Filter

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

\[ \omega \]

More Practical Filter

Simplest Filter

First-Order RC Filter (LPF1)

\[ H(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{1}{1 + \frac{s}{\omega_0}} \]

\[ \omega_0 = \frac{1}{RC} = 2\pi \times 100kHz \]
### Poles and Zeros

**s-plane (pzmap):**

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

- **Pole:** $p = -\omega_o$
- **Zero:** $z \to \infty$

$$|H(s)| = \left| \frac{1}{1 + j \frac{\omega}{\omega_o}} \right| = \sqrt{\frac{1}{1 + \frac{\omega^2}{\omega_o^2}}}$$

### Filter Frequency Response

**Bode Plot**

$$|H(s = j\omega)|_{\omega = 0} = 1$$

$$|H(s = j\omega)|_{\omega = \omega_o} = \frac{1}{\sqrt{2}}$$

$$|H(s = j\omega)|_{\omega \to \infty} = 0$$

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

**Question:**
can we really get 100dB attenuation at 10GHz?
First-Order Low-Pass 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

\[
\overline{v_n^2} = 4k_B T R \Delta f
\]

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:

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

Good numbers to memorize:

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

- Scaling $R$:
  - A 10MΩ resistor gives 400nV/$\sqrt{\text{Hz}}$
  - A 50Ω resistor gives 0.9nV/$\sqrt{\text{Hz}}$

- Or, remember

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

- 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.

\[
\overline{v_o^2} = \int_{f_1}^{f_2} \overline{v_n^2} |H(j\omega)|^2 \, df
\]
\[
\overline{v_o^2} = \int_{f_1}^{\infty} 4k_B T R |H(2\pi jf)|^2 \, df
\]

*Ref: “Analysis & Design of Analog Integrated Circuits”, Gray, Hurst, Lewis, Meyer- Chapter 11*
Total Noise

\[
\overline{v_n^2} = \int_0^\infty 4kT R |H(2\pi jf)|^2 df = \int_0^\infty 4kT R \left| \frac{i}{1+2\pi jfRC} \right|^2 df \rightarrow \overline{v_n^2} = \frac{kT}{C}
\]

- 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, \( \sqrt{kT/C} = 64 \mu V\text{-rms} \) (at 298\°K)
- 1000pF gives 2 \( \mu V\text{-rms} \)
- 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

$$V_{\text{max}}(\text{rms}) = \frac{1}{\sqrt{2}} \frac{V_{DD}}{2}$$

- Noise for a filter:

$$V_n(\text{rms}) = \sqrt{\frac{kT}{C}}$$

$$D.R. = \frac{V_{\text{max}}(\text{rms})}{V_n(\text{rms})} = \frac{V_{DD} \sqrt{C}}{\sqrt{8 \alpha kT}} \quad \text{[V/V]}$$

→ Dynamic range in dB is:

$$20 \log_{10} \left( V_{DD} \sqrt{\frac{C}{\alpha}} \right) + 75 \quad \text{[dB]} \text{ with } C \text{ in } \text{[pF]}$$
Analog Circuit Dynamic Range

• For integrated circuits built in modern CMOS processes, $V_{DD} < 3V$ and $C < 100pF$ ($\alpha = 1$)
  
  – $D.R. < 104\, dB$

• For PC board circuits built with “old-fashioned” $30V$ opamps and discrete capacitors of $< 100nF$
  
  – $D.R. < 140db$
  
  – A 36\, dB advantage!

Dynamic Range versus Number of Bits

• Number of bits and dB are related:

$$D.R. = (1.76 + 6.02N) \, [dB] \quad N \rightarrow \text{number of bits}$$

  – see “quantization noise”, later in the course

• Hence

$$104\, dB \quad \rightarrow \quad 17\, \text{Bits}$$

$$140\, dB \quad \rightarrow \quad 23\, \text{Bits}$$
Dynamic Range versus Power Dissipation

- Each extra bit corresponds to 6dB
- Increasing dynamic range by one bit → 6dB less noise → decrease in 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 $V_{\text{dsat}}$)

In analog circuits with performance limited by thermal noise, 1 extra bit costs 4x power

E.g. 16Bit ADC at 200mW → 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 significant levels of extra noise to overall filter noise
- Reducing noise in most analog circuits costs in terms of power dissipation and chip area