EE247
Lecture 27

• Today:
  – \( \Sigma \Delta \) Modulator (continued)
  – Examples of systems utilizing analog-digital
  – Acknowledgements

Oversampled Converters
Cont’d

• Higher order \( \Sigma \Delta \) modulators
  – Single-loop single-quantizer modulators with multi-order filtering in the forward path
  – Example: 5\(^{th}\) order \( \Sigma \Delta \)
    – Modeling
    – Noise shaping
    – Complex loop filters
    – Stability
    – Voltage scaling, input range scaling
    – Tones, Dither, \( kT/C \) noise
      – Interference via \( V_{ref} \)
      – Effect of component nonlinearities on \( \Sigma \Delta \) performance
Recap

- Dither successfully removes in-band tones that would corrupt the signal
- The high-frequency tones in the quantization noise spectrum will be removed by the digital filter following the modulator
- What if some of these strong tones are demodulated to the base-band prior to digital filtering?
- Why would this happen?
  → Vref Interference

Modulation via DAC

\[
y(t) = P_{out} = \pm 1 \\
V_{ref} = 2.5V + \text{Im} V \quad f_s/2 \text{ square wave} \\
v(t) = y(t) \times V_{ref}
\]
Modulation via DAC

\[ D_{\text{OUT}} \text{ spectrum} \]

\[ V_{\text{ref}} \text{ spectrum} \]

interferer

\[ \text{convolution yields sum of red and green, mirrored tones and noise appear in band} \]

0 \[ f_s/2 \]
\[ f_s \]

**V_{\text{ref}}** Interference via Modulation

Key Point:
In high resolution ΣΔ modulators → V_{ref} interference via modulation can significantly limit the maximum dynamic range

Output Spectrum [dBWN]

Frequency [kHz]

-150 -100 0 50

-60dB (1 dB/\text{dB})
Symmetry of the spectra at $f_s/2$ and DC confirm that this is modulation.

\[ V_{\text{ref}} \] Interference via Modulation

\[ V_{\text{ref}} \] Spurious Tone Velocity vs. Native Tone Velocity

- Native tone velocity $\rightarrow 1.2\text{kHz/mV}$
- Aliased tone velocity $\rightarrow 0.6\text{kHz/mV}$
• Simulations performed to verify the effect of the DAC reference contamination via output signal interference particularly in the vicinity of $f_s/2$

• Interference modulates the high-frequency tones

• Since the high frequency tones are strong, a small amount ($1\mu V$) of interference suffice to create audible base-band tones

• Stronger interference ($1mV$) not only aliases spurious tones but elevate noise floor by aliasing high frequency quantization noise

• Amplitude of modulated tones is proportional to interference

• The velocity of modulated tones is half that of the native tones

• Such differences help debugging of silicon

• How clean does the reference have to be?

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**$V_{ref}$ Interference via Modulation**

- Output Spectrum ($1\mu V$ interference on $V_{ref}$)
- Integrated Noise (30 averages)

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**$V_{ref}$ Interference**

- Tones dominate noise floor w/o thermal noise
Summary

- Our stage 2 model can drive almost all capacitor sizing decisions
  - Gain scaling
  - kT/C noise
  - Dither

- Dither quite effective in the elimination of native in-band tones

- Extremely clean & well-isolated $V_{ref}$ is required for high-dynamic range applications e.g. digital audio

- Next we will add relevant component imperfections:
  - Effect of component nonlinearities on $\Sigma\Delta$ performance

Modeling $\Sigma\Delta$ Nonlinearities

- Many component nonlinearities contribute errors
  - Important to identify the ones which incur significant errors and analyze those only
  - Unnecessarily complex models reduce the chance to find relevant problems, and perhaps, solutions
  - As with all nonidealities, model one at a time

- Expect errors from the 2nd integrator to be reduced by the gain of the 1st integrator
  - Errors further downstream are even less significant
Effect of Component Non-Linearity

→ 1st Integrator nonlinearity most significant impact on ΣΔ linearity/noise performance

1st Integrator

- Key non-linear component effects to be analyzed:
  - $C_{IN}$ – Since not enclosed in feedback loop → high impact
  - Opamp closed-loop transfer characteristic
  - $C_{FB}$ – not quite obvious - will analyze
  - Switch charge injection
Capacitor Voltage Coefficient

- Ideal capacitor
  \[ Q = CV \]

- Practical capacitor (1st order model)
  \[ Q = C(V)V \quad \text{with} \quad Q(V) = C_c(1 + \alpha V + \ldots)V \]

- Typical voltage coefficients
  - Poly-poly capacitors \(~20\) ppm/V
  - Metal-metal capacitors \(1 \ldots 10\) ppm/V

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**C\text{IN} Voltage Coefficient**

- Charge conservation dictates: \(V_{CM}=0, C_{R1}=C_{R2}=C_R\):

\[
V_{IOUT}(k) = V_{IOUT}(k-1)
\underbrace{\text{integration}}_{\text{converter input}} + \frac{C_{IN}V_{IN}(k-1) + \alpha C_{IN}V_{IN}^2(k-1)}{C_{FB}} - D\frac{C_R}{C_{FB}}V_{REF}
\underbrace{\text{1-bit feedback}}_{\text{integration}}
\]
C\textsubscript{IN} Voltage Coefficient

- \( V\text{\_in} = V\text{\_FS} = 1V \)
- Spectrum scaled for \( V\text{\_FS} \rightarrow 0dB \)
  (window lowers peak)
- Noise integral excludes DC, fundamental
- \( \alpha = 10 \text{ ppm/V} \)
- 2\textsuperscript{nd} harmonic at \(-105dB\) dominates noise!

Let's characterize it …

\[ \text{Output Spectrum [dBFS]} / \text{Int. Noise [dBV]} \]

\[ \text{Frequency [kHz]} \]

\[ \text{Output Spectrum} \quad \text{Integrated Noise} \]

\[ \alpha = 10 \text{ ppm/V} \quad \alpha = 1 \text{ ppm/V} \]

2\textsuperscript{nd} harmonic increases 1dB per 1dB increase of \( \alpha \)
Effect of Circuit Non-Idealities

- In principle, the digital filter removes out-of-band tones
  - Except their distortion components falling in the baseband, caused by nonlinearities in the modulator loop filter
  - Except components that are mixed down to baseband due to noise in the DAC reference

- Nonlinearities in the 1st integrator amplifier are important
- Other source of nonlinearity:
  - Feedback capacitor non-linearity
  - Switch induced distortion
  - Including those in the model is left as an exercise …
  - Effect of 3rd order non-linearities → good exercise!

- Maintaining extremely high levels of linearity in $H(z)$ is the most significant transistor-level design challenge of high resolution $\Sigma\Delta$ modulators

Summary
Oversampled ADCs

- Noise shaping utilized to reduce baseband quantization noise power
- Reduced precision requirement for analog building blocks compared to Nyquist rate converters
- Relaxed transition band requirements for analog anti-aliasing filters
- Utilizes low cost, low power digital filtering
- Speed is traded for resolution
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, Interpolating & Folding, Pipeline ADCs,….
    • Self-calibration techniques
    • Oversampled converters

Systems Including Analog-Digital Interface Circuitry
(Not Included in Final Exam)

– 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

– Disk drives
– Fiber-optic systems
### E.E. Circuit Course vs. Frequency Range

#### DC 10MHz
- Baseband
- RF Band
- IF Band
- AM Radio
- FM Radio
- Cellular Phone
- 500kHz
- 10.7MHz
- 80MHz
- 100MHz
- 455kHz
- 100MHz

#### Wireline Communications
- Telephone Based

### EE240, EE247
- EE242
Data Transmission Over Existing Twisted-Pair Phone Lines

- Data transmitted over existing phone lines covering distances close to 3.5 miles
  - Voice-band MODEMs
  - ISDN
  - HDSL, SDSL,……
  - ADSL

Data Transmission Over Twisted-Pair Phone Lines

ISDN (U-Interface) Transceiver

- Full duplex transmission (RX & TX signals sent simultaneously)
- 160kbit/sec baseband data (80kHz signal bandwidth)
- Standardized line code 2B1Q (4 level code 3:1:-1:-3)
- Max. desired loop coverage 18kft (~36dB signal attenuation)
- Final required BER (bit-error-rate) $10^{-7}$ → (min. SNDR=27dB)
Analog Front-End
Transmit Pulse Shape

Standard mandates a pulse mask \(\Rightarrow\) Ensure min. high-frequency content on the line to avoid spurious coupling into other lines

ISDN (U-Interface) Transceiver
Echo Problem

- Transformer coupling to line
  - For a perfectly matched system \(\Rightarrow\) no leakage of TX signal into RX path
  - Unfortunately, system has poor matching + complicating factor of bridged-taps
ISDN (U-Interface) Transceiver
Echo Problem

- System full duplex transmission → RX & TX signals sent simultaneous (& at the same frequency band)
  - Leakage of TX signal to RX path (echo)
  - Worst case → echo could be 30dB higher compared to the received signal!!

ISDN (U-Interface) Transceiver
Echo Cancellation

- Echo cancellation performed in the digital domain
  - Typically echo cancellation performed by transversal adaptive digital filter
  - Any non-linearity incurred by the analog circuitry makes echo canceller significantly more complex
  → Desirable to have high linearity analog circuitry (75dB range)
Simplified Transceiver Block Diagram

CMA → Control, maintenance & access unit
DFE → Decision feedback equalizer
DEC → Decimation filter
REC → Reconstruction filter
LEC & NEC → Linear/non-linear echo-canceller


Analog Front-End

To avoid stringent requirements for non-linear echo canceller:
→ high linearity analog circuitry needed (~ 75dB)

Peak signal frequency → 80kHz
Data Transmission Over Twisted-Pair Phone Lines

**DSL (Digital Subscriber Loop)**

- HDSL & SDSL more like ISDN @ higher frequencies
  - Full duplex transmission with RX & TX signals on the same frequency band
Data Transmission Over Twisted-Pair Phone Lines
ADSL (Digital Subscriber Loop)

- In USA mostly ADSL → FDM (frequency division multiplex)
  - Signal from CO to customer on a different band compared to customer to CO
    - Echo cancellation can be performed by simple filtering
  - Data rates up to 8Mbps (much higher compared to ISDN)

ADSL Signal Characteristics

- Main difference compared to ISDN: TX & RX signals on different frequency bands
  - Downstream (fast, from CO to customer) 138kHz to 1.1MHz
  - Upstream (slow, from customer to CO) 30kHz to 138kHz
    - Echo cancellation much easier
  - More severe signal attenuation at high frequencies (1MHz DSL v.s. 80kHz ISDN)
Typical ADSL Analog Front-End

- ADC 16/14b with 14bit linearity, pipeline with auto. calibration @ 4.4Ms/s
- DAC 16/14b with 14bit linearity, S.C. with auto. calibration
- On-chip filters 3rd to 4th order LPF with $f_c$ 1.1MHz for downstream and 138kHz upstream (typically continuous-time type filters with on-chip frequency tuning)


- Note: Band selection filters are off-chip due to stringent noise requirements (3nV/rtHz)
  - Discrete LC type

- Line driver on a separate bipolar chip to achieve required high output signal levels with high power efficiency
Wireless Communication Circuits

- Differ from wired comm. circuits
  - Includes RF circuitry+IF circuitry+baseband circuits (three different frequency ranges)
  - Signal scenarios in wireless receivers more challenging
  - Requirement for received signal BER in the order of $10^{-3}$ \( \rightarrow \) (min. SNR~9dB)
Typical Cellular Phone Block Diagram

Superheterodyne Receiver

- One or more intermediate frequency (IF)
- Periodic signal at a frequency equal to the desired RX signal + or – IF frequency is provided by a Local Oscillator
- RX signal is frequency shifted to a fixed frequency (IF filter center frequency)
RF Superheterodyne Receiver
Example: CDMA Receiver

- Received frequency is mixed down to a fixed IF frequency and then filtered with a bandpass filter.

Why Image Reject Filter?

- Any signal at the image frequency of the RX signal with respect to Osc. frequency will fall on the desired RX signal and cause impairment.
**Why Image Reject Filter?**

- Image reject filter attenuates signals out of the RX band
- Typically, image reject filters are ceramic or LC type filters

![Diagram of a receiver circuit with an image reject filter and a frequency synthesizer]

**Quadrature Downconversion**

- In systems with phase or freq. modulation, since signal is not symmetric around $f_{IF}$, directly converting down to baseband corrupts the sidebands
- Quadrature downconversion overcomes this problem

![Diagram of a quadrature downconversion circuit with in-phase and quadrature channel select filters]
Effect of Adjacent Channels

- Adjacent channels can be as much as 60dB higher compared to the desired RX signal!
- Linearity of stages prior and including channel selection filters extremely important

Effect of Adjacent Channels

- Due to existence of large unwanted signals & limited dynamic range for the front-end circuitry:
  - Can not amplify the signal up front due to linearity issues
  - Need to allocate amplification/filtering numbers to RX blocks carefully
  - Can only amplify when unwanted signals are filtered adequately
  - System design critical with respect to tradeoffs affecting:
    - Gain
    - Linearity
    - Power dissipation
    - Chip area
Wireless Communications
Linearity

- Most critical contributor to non-linearity in wireless communications circuits 3\textsuperscript{rd} order intermod.: 
- Two forms of linearity measurements:
  - 1dB compression point \( \rightarrow \) Useful for the cases where the desired received channel is strong 
  - 3\textsuperscript{rd} order intercept point \( \rightarrow \) Good measure for when interferers much larger compared to the desired channel 

Wireless Communications Measure of Linearity

1dB Compression Point

\[
V_{out} = \alpha_1 V_{in} + \alpha_2 V_{in}^2 + \alpha_3 V_{in}^3 + \ldots \ldots 
\]
Wireless Communications Measure of Linearity Third Order Intercept Point

\[ V_{out} = \alpha_1 V_{in} + \alpha_2 V_{in}^2 + \alpha_3 V_{in}^3 + \ldots \]

\[ IM_1 = \frac{3}{1} \text{rd} \]

\[ = \frac{3}{4} \alpha_1 V_{in}^2 + \frac{25}{8} \alpha_2 V_{in}^4 + \ldots \]

\[ = 1@\text{IP3} \]

Typically:
\[ IIP_3 = P_{dB} = 9.6dB \]

Most common measure of linearity for wireless circuits:
\[ \rightarrow OIP_3 & IIP_3, \text{ Third order output/input intercept point} \]

Homodyne (Direct to Baseband) Receivers

- No intermediate frequency, signal mixed down to baseband
- Almost all of the filtering performed at baseband
  - Higher levels of integration possible
  - Issue to be aware of:
    - Requirements for the baseband filters extremely stringent
    - Since the local oscillator frequency is exactly at the same freq. as the RX signal freq. \( \rightarrow \) can cause major DC offsets & drive the receiver front-end into non-linear region
Example: Wireless LAN 802.11b & Bluetooth


Digital IF Receiver

(IF sampling)

- IF signal is converted to digital → most of signal processing performed in the digital domain
- Performance requirement for ADC extremely demanding in terms of noise, linearity, and dynamic range!
- With advancements of ADCs could be the architecture of choice in the future
Typical Wireless Transmitter

- Transmit signal shipped from DSP to the analog front-end in the form of I&Q signals
- Signal converted to analog form by D/A
- Lowpass filter provides pulse shaping
- In-phase & Quad. Components combined and then mixed up to RF
- Power amplifier amplifies and provides the low-impedance output

Analog Filters in Super-Heterodyne Wireless Transceivers

<table>
<thead>
<tr>
<th>Filters</th>
<th>Function</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Filter</td>
<td>Image Rejection</td>
<td>Ceramic or LC</td>
</tr>
<tr>
<td>IF Filter</td>
<td>Channel selection</td>
<td>SAW</td>
</tr>
<tr>
<td>Base-band Filters</td>
<td>Channel Selection &amp; Anti-aliasing for ADC</td>
<td>Integrated Cont.-Time or S.C.</td>
</tr>
</tbody>
</table>
Example: Dual Mode CDMA (IS95) & Analog Cellular Phone

- Baseband analog circuitry includes:
  - CDMA
    - 4-bit flash type ADC clock rate 10MHz
    - 8-bit segmented TX DAC clock rate 10MHz (shared with FM)
    - 7th order elliptic RX lowpass filter corner freq. 650kHz
    - 3rd order Chebyshev TX lowpass filter corner freq. 650kHz
  - FM (analog)
    - 8-bit successive approximation ADCs clock rate 360kHz
    - 5th order Chebyshev RX lowpass filter corner frequency 14kHz
    - 3rd order Butterworth TX lowpass filter corner frequency 27kHz
Summary

• Examples of systems utilizing challenging analog to digital interface circuitry- in the area of wireline & wireless systems discussed
• Analog circuits still remain the interface → connecting the digital world to the real world!

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