High Speed Communication Circuits and Systems
Lecture 10
Mixers

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Mixer Design for Wireless Systems

- **Design Issues**
  - Noise Figure – impacts receiver sensitivity
  - Linearity (IIP3) – impacts receiver blocking performance
  - Conversion gain – lowers noise impact of following stages
  - Power match – want max voltage gain rather than power match for integrated designs
  - Power – want low power dissipation
  - Isolation – want to minimize interaction between the RF, IF, and LO ports
  - Sensitivity to process/temp variations – need to make it manufacturable in high volume
Ideal Mixer Behavior

- **RF spectrum converted to a lower IF center frequency**
  - IF stands for intermediate frequency
    - If IF frequency is nonzero – heterodyne or low IF receiver
    - If IF frequency is zero – homodyne receiver
- Use a filter at the IF output to remove undesired high frequency components
The Issue of Aliasing

- When the IF frequency is nonzero, there is an image band for a given desired channel band
  - Frequency content in image band will combine with that of the desired channel at the IF output
  - The impact of the image interference cannot be removed through filtering at the IF output!
**LO Feedthrough**

- LO feedthrough will occur from the LO port to IF output port due to parasitic capacitance, power supply coupling, etc.
  - Often significant since LO output much higher than RF signal
    - If large, can potentially desensitize the receiver due to the extra dynamic range consumed at the IF output
    - If small, can generally be removed by filter at IF output
Reverse LO Feedthrough

- Reverse LO feedthrough will occur from the LO port to RF input port due to parasitic capacitance, etc.
  - If large, and LNA doesn’t provide adequate isolation, then LO energy can leak out of antenna and violate emission standards for radio
  - Must insure that isolate to antenna is adequate
Self-Mixing of Reverse LO Feedthrough

- LO component in the RF input can pass back through the mixer and be modulated by the LO signal
  - DC and 2f₀ component created at IF output
  - Of no consequence for a heterodyne system, but can cause problems for homodyne systems (i.e., zero IF)
Removal of Image Interference – Solution 1

- An image reject filter can be used before the mixer to prevent the image content from aliasing into the desired channel at the IF output.

- Issue – must have a high IF frequency
  - Filter bandwidth must be large enough to pass all channels
  - Filter Q cannot be arbitrarily large (low IF requires high Q)
Removal of Image Interference – Solution 2

- Mix directly down to baseband (i.e., homodyne approach)
  - With an IF frequency of zero, there is no image band
- Issues – many!
  - DC term of LO feedthrough can corrupt signal if time-varying
  - DC offsets can swamp out dynamic range at IF output
  - $1/f$ noise, back radiation through antenna
Removal of Image Interference – Solution 3

- Rather than filtering out the image, we can cancel it out using an image rejection mixer
  - Advantages
    - Allows a low IF frequency to be used without requiring a high Q filter
    - Very amenable to integration
  - Disadvantage
    - Level of image rejection is determined by mismatch in gain and phase of the top and bottom paths
    - Practical architectures limited to 40-50 dB image rejection
**Image Reject Mixer Principles – Step 1**

- **Note:** we are assuming RF in(f) is purely real right now
Image Reject Mixer Principles – Step 2

![Image Reject Mixer Diagram]

- RF in(f)
- Image Interferer
- Desired channel

\[
\begin{align*}
a(t) &= 2\cos(2\pi f_1 t) \\
b(t) &= 2\sin(2\pi f_1 t) \\
c(t) &= 2\cos(2\pi f_2 t) \\
d(t) &= 2\sin(2\pi f_2 t) \\
e(t) &= \text{Lowpass} \\
g(t) &= \text{Lowpass} \\
\text{IF out} &= a(t) + b(t) - c(t) - d(t)
\end{align*}
\]

- C(f)
- D(f)
Image Reject Mixer Principles – Step 3

\[ e(t) = 2\cos(2\pi f_2 t) \]
\[ g(t) = 2\sin(2\pi f_2 t) \]

\[ c(t) \]
\[ d(t) \]

\[ e(t) \]
\[ g(t) \]

\[ C(f) \]
\[ D(f) \]

\[ 0 \]
\[ f \]
\[ f_2 \]
\[ -f_2 \]

\[ E(f) \]
\[ G(f) \]

\[ 0 \]
\[ f \]
\[ f_2 \]
\[ -f_2 \]

\[ 1 \]
\[ 2 \]
\[ -1 \]
\[ -2 \]

\[ j \]
\[ -j \]
Image Reject Mixer Principles – Step 4
For all analog architecture, going to zero IF introduces sensitivity to 1/f noise at IF output
- Can fix this problem by digitizing c(t) and d(t), and then performing final mixing in the digital domain
- Can generate accurate quadrature sine wave signals by using a frequency divider
What if RF in(f) is Purely Imaginary?

- Both desired and image signals disappear!
  - Architecture is sensitive to the phase of the RF input

- Can we modify the architecture to fix this issue?
**Modification of Mixer Architecture for Imaginary RF in(f)**

- **Desired channel now appears given two changes**
  - Sine and cosine demodulators are switched in second half of image rejection mixer
  - The two paths are now added rather than subtracted
- **Issue – architecture now zeros out desired channel when RF in(f) is purely real**

\[ \begin{align*}
  &\text{Desired channel} \\
  &\text{Image Interferer} \\
  &\text{RF in(f)} \\
  &\text{RF in(f)} \\
\end{align*} \]

\[ \begin{align*}
  &a(t) \quad 2\cos(2\pi f_1 t) \\
  &b(t) \quad 2\sin(2\pi f_1 t) \\
  &c(t) \quad \text{Lowpass} \\
  &d(t) \quad \text{Lowpass} \\
  &e(t) \quad + \\
  &g(t) \quad + \\
\end{align*} \]

\[ \begin{align*}
  &\text{IF out}(f) \\
  &\text{IF out}(f) \\
  &\text{IF out}(f) \\
  &\text{IF out}(f) \\
\end{align*} \]
Overall Mixer Architecture – Use I/Q Demodulation

- Both real and imag. parts of RF input now pass through
Mixer Single-Sideband (SSB) Noise Figure

- **Issue** – broadband noise from mixer or front end filter will be located in both image and desired bands
  - Noise from both image and desired bands will combine in desired channel at IF output
    - Channel filter cannot remove this
  - Mixers are inherently noisy!

\[
\begin{align*}
\text{RF in}(f) & \quad \text{Desired channel} \\
\text{LO out}(f) & \quad \Delta f \\
\text{IF out}(f) & \quad 2N_o \\
\end{align*}
\]
Mixer Double-Sideband (DSB) Noise Figure

- For zero IF, there is no image band
  - Noise from positive and negative frequencies combine, but the signals do as well
- DSB noise figure is 3 dB lower than SSB noise figure
  - DSB noise figure often quoted since it sounds better
- For either case, Noise Figure computed through simulation
Square waves are easier to generate than sine waves

- How do they impact the mixing operation when used as the LO signal?
- We will briefly review Fourier transforms (series) to understand this issue

$$\text{Local Oscillator Output} = 2\text{sgn}(\cos(2\pi f_0 t))$$
Two Important Transform Pairs

- Transform of a rectangle pulse in time is a sinc function in frequency

- Transform of an impulse train in time is an impulse train in frequency
Decomposition of Square Wave to Simplify Analysis

- Consider now a square wave with duty cycle $W/T$

- Decomposition in time
Associated Frequency Transforms

- Consider now a square wave with duty cycle $W/T$

- Decomposition in frequency
Overall Frequency Transform of a Square Wave

- Resulting transform relationship

- Fundamental at frequency $1/T$
  - Higher harmonics have lower magnitude

- If $W = T/2$ (i.e., 50% duty cycle)
  - No even harmonics!

- If amplitude varies between 1 and -1 (rather than 1 and 0)
  - No DC component
**Analysis of Using Square-Wave for LO Signal**

- Each frequency component of LO signal will now mix with the RF input
  - If RF input spectrum sufficiently narrowband with respect to $f_o$, then no aliasing will occur
- Desired output (mixed by the fundamental component) can be extracted using a filter at the IF output

$$f - fo \leq fo = 2\text{sgn}(\cos(2\pi f_o t))$$
Voltage Conversion Gain

- Defined as voltage ratio of desired IF value to RF input
- Example: for an ideal mixer with RF input = $A\sin(2\pi(f_o + \Delta f)t)$ and sine wave LO signal = $B\cos(2\pi f_o t)$

\[
IF_{out}(t) = \frac{AB}{2} \left( \cos(2\pi(\Delta f)t) + \cos(2\pi(2f_o + \Delta f)t) \right)
\]

⇒ Voltage Conversion Gain = $\frac{AB/2}{A} = \frac{B}{2}$

- For practical mixers, value depends on mixer topology and LO signal (i.e., sine or square wave)
Impact of High Voltage Conversion Gain

- **Benefit of high voltage gain**
  - The noise of later stages will have less of an impact

- **Issues with high voltage gain**
  - May be accompanied by higher noise figure than could be achieved with lower voltage gain
  - May be accompanied by nonlinearities that limit interference rejection (i.e., passive mixers can generally be made more linear than active ones)
Impact of Nonlinearity in Mixers

- Ignoring dynamic effects, we can model mixer as nonlinearities around an ideal mixer
  - Nonlinearity A will have the same impact as LNA nonlinearity (measured with IIP3)
  - Nonlinearity B will change the spectrum of the LO signal
    - Causes additional mixing that must be analyzed
    - Changes conversion gain somewhat
  - Nonlinearity C will cause self mixing of IF output
Primary Focus is Typically Nonlinearity in RF Input Path

- **Nonlinearity B** not detrimental in most cases
  - LO signal often a square wave anyway
- **Nonlinearity C** can be avoided by using a linear load (such as a resistor)
- **Nonlinearity A** can hamper rejection of interferers
  - Characterize with IIP3 as with LNA designs
  - Use two-tone test to measure (similar to LNA)
The Issue of Balance in Mixers

- A balanced signal is defined to have a zero DC component
- Mixers have two signals of concern with respect to this issue – LO and RF signals
  - Unbalanced RF input causes LO feedthrough
  - Unbalanced LO signal causes RF feedthrough
- Issue – transistors require a DC offset
Achieving a Balanced LO Signal with DC Biasing

- Combine two mixer paths with LO signal 180 degrees out of phase between the paths

- DC component is cancelled
Works by converting RF input voltage to a current, then switching current between each side of differential pair

Achieves LO balance using technique on previous slide  
- Subtraction between paths is inherent to differential output

LO swing should be no larger than needed to fully turn on and off differential pair  
- Square wave is best to minimize noise from M₁ and M₂

Transconductor designed for high linearity
Transconductor Implementation 1

- Apply RF signal to input of common source amp
  - Transistor assumed to be in saturation
  - Transconductance value is the same as that of the transistor
- High $V_{\text{bias}}$ places device in velocity saturation
  - Allows high linearity to be achieved
Transconductor Implementation 2

- Apply RF signal to a common gate amplifier
- Transconductance value set by inverse of series combination of $R_s$ and $1/g_m$ of transistor
  - Amplifier is effectively degenerated to achieve higher linearity
- $I_{bias}$ can be set for large current density through device to achieve higher linearity (velocity saturation)
Transconductor Implementation 3

- Add degeneration to common source amplifier
  - Inductor better than resistor
    - No DC voltage drop
    - Increased impedance at high frequencies helps filter out undesired high frequency components
  - Don’t generally resonate inductor with $C_{gs}$
    - Power match usually not required for IC implementation due to proximity of LNA and mixer
**LO Feedthrough in Single-Balanced Mixers**

- **DC component of RF input causes very large LO feedthrough**
  - Can be removed by filtering, but can also be removed by achieving a zero DC value for RF input
### Double-Balanced Mixer

- **DC values of LO and RF signals are zero (balanced)**
- **LO feedthrough dramatically reduced!**
- **But, practical transconductor needs bias current**
Achieving a Balanced RF Signal with Biasing

- Use the same trick as with LO balancing
Double-Balanced Mixer Implementation

- Applies technique from previous slide
  - Subtraction at the output achieved by cross-coupling the output current of each stage
Gilbert Mixer

- Use a differential pair to achieve the transconductor implementation
- This is the preferred mixer implementation for most radio systems!
Transistors are alternated between the off and triode regions by the LO signal
- RF signal varies resistance of channel when in triode
- Large bias required on RF inputs to achieve triode operation

High linearity achieved, but very poor noise figure
Passive Mixers

- We can avoid the transconductor and simply use switches to perform the mixing operation
  - No bias current required allows low power operation to be achieved
- You can learn more about it in Homework 4!
Square-Law Mixer

- Achieves mixing through nonlinearity of MOS device
  - Ideally square law, which leads to a multiplication term
    \[(V_{RF} + V_{LO})^2 = V_{RF}^2 + 2V_{RF}V_{LO} + V_{LO}^2\]
  - Undesired components must be filtered out
- Need a long channel device to get square law behavior
- Issue – no isolation between LO and RF ports
**Alternative Implementation of Square Law Mixer**

- Drives LO and RF inputs on separate parts of the transistor
  - Allows some isolation between LO and RF signals
- Issue - poorer performance compared to multiplication-based mixers
  - Lots of undesired spectral components
  - Poorer isolation between LO and RF ports