Mixer
Mixer References

• “A Parallel Structure for CMOS Four-Quadrant Analog Multipliers and Its Application to a 2GHz Down-conversion Mixer” by Hsiao and Wu.
• “A Low Voltage Bulk Driven Down-conversion Mixer Core” by Kathiresan and Toumazou, 1999.
References

References

• “A Blocker-Tolerant, Noise-Cancelling Receiver Suitable for Wideband Wireless Applications,” David Murphy et al. JSSC 2012”
Tradeoffs in RX

• Noise Figure (Sensitivity)

• Distortion (Linearity)

• Phase Noise (Aliasing)
Review: Homodyne versus Heterodyne

- Heterodyne
  \[ \omega_{rf} - \omega_{lo} = \pm \omega_{if} \]

- Homodyne
  \[ \omega_{rf} - \omega_{lo} = 0 \]
Heterodyne: High-side injection

\[ \omega_{rf, N} = \omega_{lo, N} - 1 \]

- LO is above the RF tone
- Image frequency (IM) is above the LO tone

\[ \omega_{im, N} = \omega_{lo, N} + 1 \]
**Heterodyne: Low-side injection**

\[
\omega_{rf,N} = \omega_{lo,N} + 1
\]

- LO is below the RF tone
- Image frequency (IM) is below the LO tone

\[
\omega_{im,N} = \omega_{lo,N} - 1
\]
• N-path filtering translates the baseband impedance to higher frequency (more on this later)
• Impedance loads LNA and provides gain to desired band while blocking on out-of-band signals.
• Mixer is a “voltage-mode” operation.
• Gm cell produces an RF current to go through the mixer.
• Mixer is a “current-mode” operation.
• Avoids large voltage gain at RF and filters out-of-band at baseband.
Mixer-First Architecture

- N-path filtering presents a high-impedance to the antenna
- Avoids linearity problems of LNA by putting mixer at front-end
- Costs is noise figure.
Mixer Noise

• How do we cascade the noise contribution of a mixer?

• For homodyne,

\[
F_{DSB} = 1 + \frac{N_{\text{added}}}{kT f G_{LNA}}
\]

• For heterodyne,

\[
F_{SSB} = \left( 1 + \frac{G_{IM \text{ IF}}}{G_{RF \text{ IF}}} \right) \left( 1 + \frac{N_{\text{added}}}{(G_{IM \text{ IF}} + G_{RF \text{ IF}})kT f} \right)
\]

\[
= \frac{G_{RF \text{ IF}} + G_{IM \text{ IF}}}{G_{RF \text{ IF}}} + \frac{N_{\text{added}}}{G_{LNA}kT f}
\]

Notes: This is the single sideband noise figure (SSB NF) and is at least 3dB. Please remember that SSB noise figure is generally 3 dB higher than double sideband (DSB) noise figure.
Pulse Waveform

- Spectral Components of LO waveform

\[ V_{LO} = v_{LO} p(t) \]
\[ p(t) = a_0 + \sum_{k=1}^{\infty} a_k \cos(k_{LO} t) \]
\[ a_0 = Ad \quad a_k = \frac{2A}{k} \sin(k_{LO} d) \]

©James Buckwalter
LO Waveform in Mixer

\[ V_{LO}(t) = V_{pk} \frac{2\sin\left(\frac{n \cdot d}{n}\right)}{n} \cos(n \cdot LO \cdot t) \]

- Noise factor degraded by images around harmonics.
Pulse Waveform

- Some special cases...

\[ p(t) = \frac{1}{2} + 2 \cos(\frac{\pi}{2} t) + \frac{4}{3} \cos(3 \frac{\pi}{2} t) + \frac{4}{5} \cos(5 \frac{\pi}{2} t) \ldots \]

- \( d = \frac{1}{2} \)

\[ p(t) = \frac{1}{4} + \sqrt{2} \cos(\frac{\pi}{4} t) + \frac{\sqrt{2}}{3} \cos(3 \frac{\pi}{4} t) + \frac{\sqrt{2}}{5} \cos(5 \frac{\pi}{4} t) + \frac{\sqrt{2}}{7} \cos(7 \frac{\pi}{4} t) \ldots \]

- \( d \to 0 \) we approach an infinite train of delta functions.
Mixers: Switching Operation

Note that “S” is a generic signal. Could be voltage or current?

\[ S_{out} = S_{RF} \cos(\omega_{RF} t) \]

\[ S_{out} = S_{RF} \cos(\omega_{RF} t) \otimes \left\{ \frac{4}{3} \cos(3 \cdot \omega_{LO} t) + \frac{4}{5} \cos(5 \cdot \omega_{LO} t) + ... \right\} \]

\[ S_{out} = S_{RF} \cos(\omega_{RF} t) \]

©James Buckwalter
**Mixer Gain**

\[ V_{out} = (I_{DC} + I_{\text{sig}}) R_L \quad SW(t) \]

\[ I_{\text{sig}} = G_M V_{RF} \]

\[ G_M = \frac{1}{2R_S} \left( \frac{\omega_T}{\omega} \right) \]

\[ 0 \to \frac{T_{LO}}{2} : V_{out} = V_{cc} \left( I_{DC} + I_{\text{sig}} \right) R_L \]

\[ V_{cc} = \left( I_{DC} + I_{\text{sig}} \right) R_L \]

\[ \frac{T_{LO}}{2} \to T_{LO} : V_{out} = V_{cc} \left[ V_{cc} \left( I_{DC} + I_{\text{sig}} \right) R_L \right] = \left( I_{DC} + I_{\text{sig}} \right) R_L \]
Mixer Noise Analysis

- Noise analysis of a single balanced mixer:

\[ V_{LO} \]

\[ R_L \]

\[ V_{out} \]

\[ M2 \]

\[ +V_{LO} \]

\[ I_{DC,mix} + I_{RF} + I_{Noise} \]

\[ V_{RF} \]

\[ M1 \]

\[ -V_{LO} \]

\[ M3 \]
Mixer Noise Analysis

- Noise analysis of a single balanced mixer cont...:

![Mixer Diagram]

- If the switching is not instantaneous, additional noise from the switching pair will be added to the mixer output.
- Let us examine this in more detail.
Mixer Noise Analysis

- Noise analysis of a single balanced mixer cont...

When M2 is on and M3 is off:
  - M2 does not contribute any additional noise (M2 acts as cascode)
  - M3 does not contribute any additional noise (M3 is off)
Mixer Noise Analysis

- Noise analysis of a single balanced mixer cont...:

- When M2 is off and M3 is on:
  - M2 does not contribute any additional noise (M2 is off)
  - M3 does not contribute any additional noise (M3 acts as cascode)
Mixer Noise Analysis

- Noise analysis of a single balanced mixer cont...:

- When \( V_{LO}^+ = V_{LO}^- \) (i.e. the LO is passing through zero), the noise contribution from the transducer (M1) is zero. Why?
- However, the noise contributed from M2 and M3 is not zero because both transistors are conducting and the noise in M2 and M3 are uncorrelated.

©James Buckwalter
Mixer Noise Analysis

- Optimizing the mixer (for noise figure):
  - Design the transducer for minimum noise figure.
  - Noise from M2 and M3 can be minimized through fast switching of M2/M3 by:
    - making LO amplitude large
    - making M2 and M3 small (i.e. increasing $f_T$ of M2 and M3)
  - Noise from M2 and M3 can be increased by using large M2/M3 switches.

\[ \begin{align*}
V_{\text{out}} &\quad R_L \quad M2 \quad \text{on} \quad V_{LO} \\
&\quad &\quad &\quad &\quad &\quad &\quad \\
V_{\text{RF}} &\quad M1 &\quad &\quad &\quad &\quad &\quad \\
&\quad &\quad &\quad &\quad &\quad &\quad \\
V_{\text{out}} &\quad R_L \quad M3 \quad \text{on} \quad -V_{LO}
\end{align*} \]

\[ I_{\text{DC, mix}} + I_{RF} + I_{\text{Noise}} \]

\[ g_m \propto \sqrt{W} \ldots \text{fixed} - I_{\text{DC}} \]

\[ \omega_T \propto \frac{1}{\sqrt{W}} \ldots \text{fixed} - I_{\text{DC}} \]

©James Buckwalter
Mixer Noise Analysis

• Noise Figure Calculation:

$$V_{out} = V_{LO} + V_{RF} - V_{LO} + I_{DC,mix} + I_{RF} + I_{Noise}$$

• Let us calculate the noise figure including the contribution of M2/M3 during the switching process.
Heterodyne Mixer Noise Analysis: RL Noise

- Noise Analysis of Heterodyne Mixer (RL noise):

$$v_{noise-RL}^2 = 4kT(2R_L)$$

$M1$ $+V_{LO}$ $M2$ $V_{out}$ $M3$ $-V_{LO}$ $V_{RF}$ $I_{DC,mix} + I_{RF} + I_{Noise}$

©James Buckwalter
Heterodyne Mixer Noise Analysis: Transducer Noise

- Noise Analysis of Heterodyne Mixer (Transducer noise):

\[ i_{\text{noise } M_1 \text{ switch}} = i_{\text{noise } M_1}(t) \cdot \text{SW}(t) \]

\[ = i_{\text{noise } M_1}(t) \left( \frac{4}{3} \cos\left\{ 3 \ LO t \right\} + \frac{4}{5} \cos\left\{ 5 \ LO t \right\} + \ldots \right) \]
Heterodyne Mixer Noise Analysis: Transducer Noise

- Noise Analysis of Heterodyne Mixer (Trans-conductor noise):

\[ i_{\text{noise } M_1 \text{ switch}} = i_{\text{noise } M_1} (t) SW(t) \]

\[ = i_{\text{noise } M_1} (t) \left( \frac{4}{3} \cos \{ 3 \omega_{LO} t \} + \frac{4}{5} \cos \{ 5 \omega_{LO} t \} \right) \]

\[
\frac{1}{n^2} = \frac{2}{8} \quad \text{for } n=1, \text{odd}
\]

\[
\overline{i_{\text{noise } M_1}^2 (f)} = 4kT \ g_{do,1}
\]

\[
\overline{i_{\text{noise } M_1}^2 (IF)} = 2 \left( \frac{4}{4} \right)^2 \left[ 1 + \frac{1}{3^2} + \frac{1}{5^2} + \ldots \right] 4kT \ g_{do,1}
\]

\[
SW(f) = \frac{4}{f} \left( f - f_{LO} \right) + \frac{4}{3} \left( f - 3f_{LO} \right) + \ldots
\]

\[
\overline{i_{\text{noise } M_1}^2 (f)} = 4 \times 4kT \ g_{do,1}
\]
Heterodyne Mixer Noise Analysis: Switch Noise

- Noise Analysis of Heterodyne Mixer (switch noise):

\[ \bar{i}_d^2 = 4kT g_m \]

\[ \bar{v}_{gn}^2 = \frac{4kT}{g_m} \]

\[ i_{d,2}^2 + i_{d,3}^2 \]

©James Buckwalter
Heterodyne Mixer Noise Analysis: Switch Noise

- Noise Analysis of Heterodyne Mixer (switch noise):

\[ V_{LO} \pm V_{RF} \pm I_{DC,mix} + I_{RF} + I_{Noise} \]

- Show that: 
  \[ G_m = g_{m2} = g_{m3} = g_{m2,3} \approx \frac{2I_{DC,mix}}{V} \]
Heterodyne Mixer Noise Analysis: Switch Noise

- Noise Analysis of Heterodyne Mixer (switch noise) cont...:

\[ i_{out}(t) = G_m(t) \cdot v_{n-m2,3}(t) \]
Heterodyne Mixer Noise Analysis: Switch Noise

- Noise Analysis of Heterodyne Mixer (switch noise) cont...:

\[ \begin{align*}
V_{LO} &= v_{LO} p(t) \\
p(t) &= a_0 + \sum_{k=1}^{\infty} a_k \cos(k \omega_{LO} t) \\
a_0 &= Ad \\
a_k &= \frac{2A}{k} \sin(k \Delta t)
\end{align*} \]

\[ 
G_m(t) = \frac{T G_{m0}}{T_{LO}/2} \left[ 1 + \sum_{k=1}^{\infty} \sin \left( k \frac{T}{T_{LO}/2} \right) \cos \left( k \omega_p t \right) \right]
\]

\[ 
v_{n-m2,3} = v_{n-m2}^2 + v_{n-m3}^2 \\
v_{n-m2,3}(f) = 2 \frac{4kT}{g_{m2,3}}
\]

\[ \omega_p = \left( \frac{2\pi}{T_{LO}/2} \right) \]
Heterodyne Mixer Noise Analysis: Switch Noise

- Noise Analysis of Heterodyne Mixer (switch noise) cont....:

\[ G_m(f) \]

\[ v_{n-m,2,3}(f) \]

\[ i_{out}(t) = G_m(t) v_{n,m2,3}(t) \]

\[ i_{noise}^2_{M,2,3}(IF) = v_{n,m2,3}^2 \left( \frac{T}{T_{LO}} \right)^2 + 2 v_{n,m2,3}^2 \left( \frac{T}{T_{LO}} \right)^2 \sum_{k=1}^{\infty} \left( \text{sinc} \left( k \frac{T}{2} \right) \right)^2 \]

How do we solve this?

©James Buckwalter
Heterodyne Mixer Noise Analysis: Switch Noise

\[
\bar{i}_{\text{noise } M,2,3}^2 (\text{IF}) = \bar{v}_{n \text{ } m,2,3}^2 \left( G_{m0} \left( \frac{T}{T_{LO}} \right) + 2 \bar{v}_{n \text{ } m,2,3}^2 \right)^2 \sum_{k=1} \left( \text{sinc} \left( k \frac{T}{2} \right) \right)^2 \]

\[
\sum_{k=1} \left( \text{sinc} \left( k \frac{T}{2} \right) \right)^2 = \frac{1 + \frac{2}{T}}{2}\]

\[
\bar{i}_{\text{noise } M,2,3}^2 (\text{IF}) = \bar{v}_{n \text{ } m,2,3}^2 \left( G_{m0} \left( \frac{T}{T_{LO}} \right) + 2 \bar{v}_{n \text{ } m,2,3}^2 \right)^2 \frac{1 + \frac{2}{T}}{2}\]

\[
\bar{i}_{\text{noise } M,2,3}^2 (\text{IF}) = \bar{v}_{n \text{ } m,2,3}^2 \left( G_{m0} \left( \frac{T}{T_{LO}} \right) + \frac{T_{LO}}{T} \right)^2 \bar{v}_{n \text{ } m,2,3}^2 G_{m0} \left( \frac{T}{T_{LO}} \right) \frac{T}{T} \]

©James Buckwalter
Heterodyne Mixer Noise Analysis: Switch Noise

- Noise Analysis of Heterodyne Mixer (switch noise) cont...:

\[
i_{\text{noise}}^{2} M_{2,3} (IF) = \frac{1}{T_{LO}^{2}} \frac{G_{m0}^{2}}{2} T_{n}^{2} v_{n,m2,3}^{2}
\]

\[
G_{m}(f) \quad v_{n-m2,3}(f)
\]

\[
\omega_p \quad 2\omega_p \quad 3\omega_p
\]
Heterodyne Mixer Noise Analysis: Switch Noise

- Noise Analysis of Heterodyne Mixer (switch noise) cont...:

\[
\frac{i^2_{\text{noise}}}{M_{2,3}}( IF ) = \frac{1}{\left( \frac{T_{\text{LO}}}{2} \right)} G^2_{m0} T v^2_{n m2,3} \quad G_m = g_{m2} = g_{m3} = g_{m2,3} \approx \frac{2I_{\text{DC,mix}}}{V}
\]

\[G_{m0} = \frac{2I_{\text{DC,mix}}}{\Delta V} \quad V = \text{Slope} \quad T \quad V_{\text{LO}}(t) = A_{\text{LO}} \cos(LO t)
\]

\[\text{Slope} \quad \omega_{\text{LO}t=90} = \left[ \frac{dV_{\text{LO}}(t)}{dt} \right]_{\omega_{\text{LO}t=90}} = A_{\text{LO}} \omega_{\text{LO}} \quad v^2_{n m2,3} = 2 \frac{4kT}{g_{m2,3}}
\]
Heterodyne Mixer Noise Analysis: Switch Noise

- Noise Analysis of Heterodyne Mixer (switch noise) cont...:

\[ i_{\text{noise } M2,3}^2 (IF) = \frac{1}{\left( \frac{T_{LO}}{2} \right)^2} G_{m0}^2 T v_{n m2,3}^2 \]

\[ i_{\text{noise } M2,3}^2 (IF) = \frac{G_{m0}^2 T}{T_{LO} / 2} v_{n m2,3}^2 = \frac{G_{m0}^2 T}{T_{LO} / 2} \left( \frac{2}{4} \frac{4kT}{g_{m2,3}} \right) \quad v_{n m2,3}^2 = 2 \frac{4kT}{g_{m2,3}} \]

\[ = 4 \frac{G_{m0}^2 T}{T_{LO}} (4kT) = 4 \frac{T}{T_{LO}} \frac{2I_{DC,\text{mix}}}{V} (4kT) \quad G_m \approx \frac{2I_{DC,\text{mix}}}{V} \]

\[ = 4 \frac{2I_{DC,\text{mix}}}{T_{LO}} \frac{T}{V} (4kT) = 4 \frac{2I_{DC,\text{mix}}}{T_{LO}} \frac{1}{A_{LO} \omega_{LO}} (4kT) \quad \frac{V}{T} = A_{LO} \omega_{LO} \]

\[ = 4 \cdot 4kT \left( \frac{I_{DC,\text{mix}}}{A_{LO}} \right) \quad \text{Total Noise Contribution due to switches M2 and M3} \]
Heterodyne Mixer Noise Analysis: Total Noise

- Noise Analysis of Heterodyne Mixer (total noise):

\[
\begin{align*}
\nu_{\text{noise-RL}}^2 &= 4kT \left(2R_L\right) \\
\nu_{\text{noise-M1}}^2 &= 4 \times 4kT g_m1 = 4 \times 4kT \frac{I_{\text{DC,mix}}}{(V_{GSQ} - V_T0)} \\
\nu_{\text{noise-M2,3}}^2 &= 4 \times 4kT \left(\frac{I_{\text{DC,mix}}}{A_{LO}}\right) \\
\nu_{\text{noise-MIX}}^2 (\omega_{\text{IF}}) &= \nu_{\text{noise-RL}}^2 + R_L^2 \frac{\nu_{\text{noise-M1}}^2}{2} + R_L^2 \frac{\nu_{\text{noise-M2,3}}^2}{4} \\
\nu_{\text{noise-MIX}}^2 (\omega_{\text{IF}}) &= 4kTR_L \left\{2 + 4 I_{\text{DC,mix}} R_L \left(\frac{1}{V_{GSQ}} - \frac{1}{V_{T0}} + \frac{1}{A_{LO}}\right)\right\}
\end{align*}
\]
Heterodyne Mixer Noise Analysis: Total Noise

- Noise Analysis of Heterodyne Mixer (total noise):

\[
\begin{align*}
\overline{v^2_{\text{noise MIX}}} (\omega_{IF}) &= 4kTR_L \left\{ 2 + 4 I_{DC,mix} R_L \left( \frac{1}{V_{GSQ} V_{T0}} + \frac{1}{A_{LO}} \right) \right\} \\
(V_{GSQ} - V_{T0}) &\uparrow \quad \Rightarrow \quad M1 - \text{linearity} \uparrow - & \& - \text{Noise} \downarrow \\
\text{As}... (V_{GSQ} - V_{T0}) &\uparrow \quad \Rightarrow \quad A_{LO} \uparrow - \text{to minimize noise contribution from } M2 / M3
\end{align*}
\]

![Graph showing the relationship between noise and LO voltage with different GSQ values](image_url)

©James Buckwalter
Heterodyne Mixer Noise Analysis: Noise Figure

\[
\frac{i^2}{i_{\text{noise-Rs}}} (\omega_{IF}) = 16kT \left( \frac{1}{2R_s} \frac{\omega_T}{\omega} \right)^2 R_s = \frac{4kT}{R_s} \left( \frac{\omega_T}{\omega} \right)^2
\]

\[
NF = \frac{V^2_{\text{noise-MIX}} (\omega_{IF})}{V^2_{\text{noise-RS}} (\omega_{IF})} = 1 + \frac{R_S}{R_L} \left( \frac{\omega}{\omega_T} \right)^2 \left[ 1 + 4\gamma I_{DC,\text{mix}} R_L \left( \frac{1}{V_{GSQ} - V_{T0}} + \frac{1}{\pi A_{LO}} \right) \right]
\]

- This assumes that all of the “white noise” from Rs is folded down. In reality, there is some matching and filtering between the generator and mixer.
Heterodyne Mixer Noise Analysis: Total Noise

- Noise Analysis of Heterodyne Mixer (total noise)--{Terrovitis and Meyer}:

\[
F = \frac{a c^2 + g 3 + r g^3 g m^3 (\big)}{g m^3 a + 2 g 1 G + R L O + 2 r g^2 (\big) G^2 + 1}{R L O}
\]

\[
\alpha \approx 1 - \frac{4}{3} \Delta T f_{LO}
\]

\[
c = \frac{2}{\pi} \sin \left( \frac{\omega_{LO} \Delta T}{2} \right)
\]

\[
\bar{G} = \frac{2 I}{A_{LO}} \quad \bar{G^2} = 4.64 \frac{K^{1/2} I_{DC,mix}^{3/2}}{2 \ A_{LO}}
\]
Homodyne Mixer Noise Analysis: Transducer Noise

- Noise Analysis of Heterodyne Mixer (Transducer noise):

\[
\begin{align*}
    V_{LO} &+ V_{LO} R_L & V_{out} \\
    +V_{LO} & M2 & V_{out} \\
    V_{RF} & M1 & I_{DC, mix} + I_{RF} + I_{Noise} \\
    -V_{LO} & M3 & \end{align*}
\]

\[
i_{\text{noise } M1 \text{ switch}} = i_{\text{noise } M1}(t) SW(t) = i_{\text{noise } M1}(t) \left( \frac{4}{3} \cos\{3 \ LO t\} + \frac{4}{5} \cos\{5 \ LO t\} + \ldots \right)
\]

©James Buckwalter
Homodyne Mixer Noise Analysis: Transducer Noise

- Noise Analysis of Heterodyne Mixer (Trans-conductor noise):

\[
i_{\text{noise } M1 \text{ switch}} = i_{\text{noise } M1}(t) SW(t)
\]

\[
= i_{\text{noise } M1}(t) \left( \frac{4}{\omega_{LO}} \cos \omega_{LO} t + \frac{4}{3} \cos 3 \omega_{LO} t + \frac{4}{5} \cos 5 \omega_{LO} t + \ldots \right)
\]

\[
\frac{1}{n^2} = \frac{2}{8}
\]

\[
i^2_{\text{noise } M1}(f) = 4kT \times g_{do,1}
\]

\[
i^2_{\text{noise } M1}(0) = 4 \div 1 + \frac{1}{3^2} + \frac{1}{5^2} + \ldots 4kT \times g_{do,1}
\]

\[
SW(f) = \frac{4}{\omega_{LO}} (f - f_{LO}) + \frac{4}{3} (f - 3f_{LO}) + \ldots
\]

\[
\frac{i^2_{\text{noise } M1}(0)}{2} = 4kT \times g_{do,1}
\]
Harmonic Rejection Mixers

• Harmonic aliases can be uniformly removed. Recall that we saw a duty cycle dependence on harmonic terms.
Harmonic Rejection Mixers

• The LO can be synthesized to remove harmonic content.

\[ s_{LO}(t) = \sum_{k=1}^{N} a_k p(t - kT) \]

\[ T = \frac{1}{f_{LO}} \frac{2(N+1)}{2(N+1)} \]
Harmonic Rejection Mixers

• When the mixer is driven with the stepped waveform

and we eliminate any aliasing of the signal on to N-1 harmonics
# Harmonic Rejection Mixer Example

<table>
<thead>
<tr>
<th>LO Phase Shift</th>
<th>No. of Square Waves</th>
<th>Square Waves</th>
<th>Harmonics Can be Cancelled</th>
</tr>
</thead>
<tbody>
<tr>
<td>45°</td>
<td>3</td>
<td>$\sqrt{2}LO(t)$, $LO(t - \pi /4)$, $LO(t + \pi /4)$</td>
<td>3rd, 5th</td>
</tr>
<tr>
<td>30°</td>
<td>5</td>
<td>$2LO(t)$, $\sqrt{3}LO(t - \pi /6)$, $\sqrt{3}LO(t + \pi /6)$, $LO(t - \pi /3)$, $LO(t + \pi /3)$</td>
<td>3rd, 5th, 7th, 9th</td>
</tr>
<tr>
<td>22.5°</td>
<td>7</td>
<td>$\sqrt{2}LO(t)$, $\sqrt{2}\cos(\pi /8)LO(t - \pi /8)$, $\sqrt{2}\cos(\pi /8)LO(t + \pi /8)$, $LO(t - \pi /4)$, $LO(t + \pi /4)$, $\sqrt{2}\sin(\pi /8)LO(t - 3\pi /8)$, $\sqrt{2}\sin(\pi /8)LO(t + 3\pi /8)$</td>
<td>3rd, 5th, 7th, 9th, 11th, 13th</td>
</tr>
</tbody>
</table>
Harmonic Rejection Mixer Implementation

- Harmonic rejection can be realized as a set of parallel RF paths or through direct frequency synthesis techniques.
Harmonic Rejection Receiver

LNTA cells (num. of unit LNTAs in each cell is shown)

Switches

CG Buffers 2nd Stage Gains

1: Gain-cell replaced by open connection

©James Buckwalter