A Dual-Mode Architecture for a Phased-Array Receiver Based on Injection-Locking in 0.13-μm CMOS

Satwik Patnaik, Narasimha Lanka, Ramesh Harjani

University of Minnesota
Outline

• Introduction
  – Phased array communication

• Motivation and proposed architecture
  – Motivation & previous architectures
  – Proposed dual-mode architecture
  – Block-level circuit design

• Measurement results
  – ILO performance
  – Radiation patterns & cross-channel leakage

• Conclusions
Phased Arrays and Frequencies

Frequency of our design

MILITARY, AEROSPACE

Cellular

0.9 1.8 2.4 5.8

(Hz)

WirelessHD

24 60 77

Automotive Radar

Satcom

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Phased Arrays: Theory

- Array of antennas → broadside directive beam
- Progressive phase-shift → agile directive beam

\[ \theta = \sin^{-1}\left(\frac{\lambda \phi}{2\pi d}\right) \]
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Previous Architectures for Phased Arrays

- Multiple VGAs → power
- VGAs at RF
  → Power hungry
- Prone to mismatch

- Removes need for mixer
- Limited scalability
  - Frequency & elements
- Phase range limited

Paramesh et. al, ISSCC’05

Krishnaswamy et. al, ISSCC’07
Previous Architectures (cont.)

- **Large number of ADCs**
  - \( \# \text{ADCs} = \# \text{elements} \)
  - Significant power, area
- **Dynamic range issues**

- **RF phase-shifting**
  - Challenge in silicon
- **Reduced linearity**
  - Needed for LNA, mixer…

Digital beam-forming

RF-phase shifting
Phased Arrays in Silicon

• Previously, phased arrays designed in III-V
  – $f_T$, $f_{\text{max}}$ used to be better than CMOS
  – High power handling capability

• Today CMOS and BiCMOS have $f_T$, $f_{\text{max}}$ of 200+ GHz

• Benefits of designing phased arrays in silicon
  – Capability of handling mm-wave frequencies
  – Significant digital post-processing possible at low “cost”
  – High level of integration possible
    • 8-element and 16-element systems already demonstrated
  – Lower wafer costs than III-V technologies
  – Better yields, less variability
Injection-Locked Oscillators (ILOs)

- Frequency synchronization of an oscillator by applying an external signal is *injection locking*
- Steady state frequency of oscillator is $\omega_{inj}$
  - $\omega_{inj}$ should be within lock-range of ILO
- Phase noise of injection signal $\rightarrow$ phase noise of ILO

Natural Frequency

$$\omega_o = \frac{1}{\sqrt{LC}}$$
Steady-State Phase in ILO

Adler’s equation for ILOs

\[
\frac{d\phi(t)}{dt} = (\omega_0 - \omega_{inj}) - \omega_L \sin[\phi(t)]
\]

\[
\omega_L = \frac{\omega_0}{2Q} \left( \frac{I_{inj}}{I_{osc}} \right)
\]

Constant phase shift generated at steady-state

\[
(\angle V_{ILO} - \angle V_{inj}) = \phi_{ss} = \sin^{-1} \left( \frac{\omega_0 - \omega_{inj}}{\omega_L} \right)
\]

\[\phi(t) = (\angle V_{ILO} - \angle V_{inj})\]
ILOs in Phased Array Systems

- Injection-locking used before in phased arrays
  - Injection signal applied through antenna coupling
    - Weak injection $\rightarrow$ low lock range $\rightarrow$ ILO may be unlocked
- Phase generated by varying end-element frequencies
  
  (Technique not viable for integrated systems in CMOS)
Proposed Architecture

- ILO creates phase between injected and output signal
  - Can be used as a phase generation mechanism

- VCO natural frequency ($\omega_0$) controls output phase
  - Phase-frequency relationship $\rightarrow$ non-linear
  - Good frequency resolution $\rightarrow$ good phase resolution
**Architecture-I: Fully Flexible**

**Advantages**
- Independent phase control
  - Arbitrary radiation patterns
  - Place nulls in jammer directions
- 2-D phased arrays possible

**Disadvantages**
- Requires extensive injection signal routing
- Needs look-up table
  - Oscillators $\omega_1, \omega_2, \omega_3, \ldots$
Advantages

- Cascade ILO approach
  - Natural beamforming
- Easier phase control
  - All oscillators → same $\omega_0$
- Independent of $\omega_0$ of first ILO
- 2-D phased arrays possible

Disadvantages

- Arbitrary radiation patterns not possible
Advantages of Dual-Mode Architecture

- ILOs inherently amplify the injection signal
  - And generate the required phase
  - Gain obtained more efficiently with regeneration

- ILOs are naturally high frequency blocks
  - Can operate very close to $f_T$

- Excellent oscillator frequency matching
  - Inductors and capacitors $\rightarrow$ better matching

- Phase control can be made virtually continuous
  - Analog or digital capacitor / varactor control

- Easy to integrate both architectures in single chip
Prototype: ILO Circuit Block

- **Frequency control**
  - 4-bit MIM cap control
    - Coarse tuning
  - Analog control for varactor
    - Fine tuning

- **Independent control for G_m-cell and oscillator bias**
  - Variable lock-range

- **ILO occupied most area**
  - Differential inductors reduce area and improve performance
Prototype: $G_m$-boosted Mixer

- **Gilbert cell mixer**
  - Uses RC-load
  - $g_m$-boosting to improve gain

- **Common-gate buffer**
  - Allows RF inputs to match 50Ω

![ gm-boosted mixer ]

![ Common-gate Buffer (50Ω) ]
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Measurements: Oscillator Tuning

- Excellent frequency matching attained
- Across 3 different chips, max. variation: 52MHz
- Within chip, max. variation: 20 MHz (<1% variation)
- Mismatch can be nulled out via varactor control
- Binary MSB cap mismatch → smaller mid-band step
Measurements: ILO

- Need enough lock-range for good frequency control
  - Large lock range → better phase control
- Lock-range mismatch → phase mismatch
  - Primary factor → injection current mismatch
Measurements: RF Input Matching

- Common-gate buffer used to match input to 50Ω
- S11 mismatch due to
  - Bond-wire length mismatch
  - External baluns also affect S11 mismatch
Test Setup: Radiation Pattern

- Simulates effect of antenna array
- Significant $\lambda$ (2.4GHz) $\rightarrow$ required T-line phase shifters
  - Measured radiation pattern using discrete phase shifters
- IF output (8MHz) measured on spectrum analyzer
- One of the four channels showed low gain (Channel-4)
  - Mixer-summer connection problem?
Radiation Patterns: Fully Flexible

- Measured 2-channel and 3-channel radiation patterns
- Excellent matching between theory and measurements

\( \theta = 0^\circ \)
- Peak-to-null: 19.1dB
- 16.1dB

\( \theta = -30^\circ \)
- Peak-to-null: 25.2dB

\( \theta = 90^\circ \)
- Peak-to-null: 21.4dB

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Radiation Patterns: Meander-Line

- Measured 2-channel and 3-channel radiation patterns
- Excellent matching between theory and measurements
- More consistent nulls $\leftrightarrow$ same $\omega_0$
Measurements: Cross-Channel Leakage

- **Test setup: no injection**
  - Four free-running VCOs
  - Different $\omega_0$

- **LO signal normally large**
  - Signal leakage affects other channels

- **Channel isolation: 26.78dB**
  - RF lines for OSC-1 and OSC-2 close on PCB

- **Spur due to LO pulling**
  - Will not occur in normal operation (same $\omega_{inj}$)
## Summary of Measured Results

### Receiver Performance

<table>
<thead>
<tr>
<th></th>
<th>2-channel</th>
<th>3-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver Gain</td>
<td>17 dB</td>
<td>20 dB</td>
</tr>
<tr>
<td>SNR Improvement</td>
<td>2-channel</td>
<td>6 dB</td>
</tr>
<tr>
<td></td>
<td>3-channel</td>
<td>9 dB</td>
</tr>
<tr>
<td>RF Frequency</td>
<td>2.4 GHz</td>
<td></td>
</tr>
<tr>
<td>IF Frequency</td>
<td>8 MHz</td>
<td></td>
</tr>
<tr>
<td>IF-amplitude error across channels</td>
<td>±1 dB</td>
<td></td>
</tr>
<tr>
<td>Suppression from Null Direction</td>
<td>&gt;25 dB</td>
<td></td>
</tr>
</tbody>
</table>

### Power Dissipation

<table>
<thead>
<tr>
<th>Component</th>
<th>Power Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO Core</td>
<td>2.67 mW (×4)</td>
</tr>
<tr>
<td>LO Buffer + $G_m$-Cell</td>
<td>4.26 mW (×4)</td>
</tr>
<tr>
<td>Downconversion Mixer</td>
<td>2.56 mW (×4)</td>
</tr>
<tr>
<td>Summer ($\Sigma$)</td>
<td>4.15 mW</td>
</tr>
<tr>
<td><strong>Total Power Consumption</strong></td>
<td><strong>42.11 mW</strong></td>
</tr>
<tr>
<td><em>(w/o bias &amp; matching circuits)</em></td>
<td><em>(10.53 mW/ch)</em></td>
</tr>
</tbody>
</table>
## Comparison to Previous Designs

<table>
<thead>
<tr>
<th></th>
<th>Area (mm²)</th>
<th>Power (mW)</th>
<th>Freq (GHz)</th>
<th>Null Suppression</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work</td>
<td>1.44</td>
<td>42</td>
<td>2.4</td>
<td>16.1-25.2 dB</td>
</tr>
<tr>
<td>Receiver in [a]</td>
<td>3.36**</td>
<td>210</td>
<td>(3X)*</td>
<td>24</td>
</tr>
<tr>
<td>[b]</td>
<td>2.62</td>
<td>84</td>
<td>(2X)*</td>
<td>5</td>
</tr>
</tbody>
</table>

[a] Krishnaswamy et al., ISSCC’07  
[b] Paramesh et al., ISSCC’05  
* Normalized for PLL and/or LNA  
** Includes PLL area
Conclusions

• Introduced two new architectures for phased arrays
  – Both architectures based on injection-locking
  – Both architectures integrated into one chip (dual mode)

• Both architectures extendable to 2-D phased arrays
  – Effortless phase control with meander-line for 1-D & 2-D

• Compact & low power
  – Lowest power phased array receiver reported
  – Area comparable to lowest area receiver

• Measured radiation patterns show excellent matching with theoretical predictions

• Easily scalable in both frequency & # of elements
For additional multimedia material: See http://www.isscc.org