Session 3 - Oscillators and PLLs

A 107 µW MedRadio Injection-Locked Clock Multiplier with a CTAT-biased 126 ppm/°C
Ring Oscillator

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The Internet of Medical Things – Io(M)T

✔ Communication to a nearby data-aggregator (e.g., smartphone, smartwatch, etc.)

✔ Miniaturized wearable sensor nodes

Ultra-Low Power Operation
A Wireless IoMT Bio-Sensor Node

- Medical Device Radiocommunications Service (MedRadio): 402-405 MHz
  - Frequency stability $\pm 100$ ppm/°C over 0 to 55 °C
  - Attenuate out-of-band/spurious emissions by 20 dBc

A Wireless IoMT Bio-Sensor Node

- Medical Device Radiocommunications Service (MedRadio): 402-405 MHz
- Duty-cycled operation
- Short-range transmitter (<2 meters TX distance)
Short-Range Transmitter

Reference Clock

RF Carrier Generation
Frequency Synthesizer / PLL

Power Amplifier

Power-hungry block
(400 MHz RF carrier)

Short-range PA
(< -17 dBm or 20 μW output power)
Injection-Locked Clock Multiplier (ILCM)

\[ F_{\text{OSC}} = N \cdot F_{\text{REF}} \]

\[ F_{\text{OSC}} < N \cdot F_{\text{REF}} \]
Prior Work – ULP Narrowband TX

- PLL-free low power TX
- Fast start-up
- Very sensitive to PVT

Robust to static PV variations
- Constant temperature assumption (close proximity to human body)
  - Loss of lock
  - Large REF spur
- Slow start-up (if calibrated each time)

Dynamic temperature variations need to be addressed
Motivation & Proposed Work

Conventional Injection-Locked Clock Multiplier (ILCM):

✓ Robust
✗ Power hungry

Proposed open-loop ILCM:

✓ Low power
✓ PVT Robust
✓ Fast-start-up
Ring Oscillator Temperature Sensitivity

Current-starved delay cell implementation

Constant-voltage bias

\[ f_{osc} \propto \frac{I_{DCO}}{C_L} \]

\[ I_{DCO,1} = I_s \cdot \exp(V_{GS}/V_T) \]

\[ (V_T \propto T) \]

\[ f_{osc} \rightarrow \text{strong PTAT} \]

Constant-current bias

\[ f_{osc} \propto \frac{I_{DCO,\text{const}}}{C_L} \]

\[ C_L: \text{negative TC} \]

(junction & MOS oxide cap.)

\[ f_{osc} \rightarrow \text{PTAT} \]

[Zhang TCAS-I ‘11], [Shrivatava CICC’12]
Temperature Compensation Concept

- Nominally, ring DCO’s free-running frequency exhibits PTAT characteristics.
- Introduce CTAT characteristics in frequency control knob.

**CTAT bias current to counteract the PTAT nature of osc. frequency**
ILCM: Circuit Implementation

- Min 3-stage ring → larger devices → lower variations
- 8-bit DCO with ±25% tuning range
CTAT Current Generation: Implementation

\[ V_{b,\text{CTAT}} = -\frac{\eta V_T \ln(N)}{2} + \frac{V_{DD}}{4} \]

\[ I_{\text{REF,CTAT}} = \frac{V_{b,\text{CTAT}}}{R_b} \]

- Low voltage, sub-threshold operation
- \( N = 24, R_b \) adds negligibly to CTAT characteristics

Adds <5% power overhead

[Choi ESSCIRC ‘14]
Delay Cell: Implementation

- Pseudo-differential delay cell
- $I_{DCO,CTAT} = I_{DCO}[k](1 - \alpha_1 \Delta T)$
- DCO current at $k^{th}$ frequency mode
- $M_{ip1}$, $M_{in2}$: injection/start-up
Delay Cell: Temperature Sensitivity

- Both junction and MOS capacitor exhibit CTAT TC
  \[ C_L = C_{L0}(1 - \alpha_C \Delta T) \]

- Using current-starved delay cell
  \[ f_{\text{osc}} \propto \frac{I_{\text{DCO,CTAT}}}{C_L} = \frac{I_{\text{DCO}}[k](1 - \alpha_1 \Delta T)}{C_{L0}(1 - \alpha_C \Delta T)} \]

TC cancellation independent of \( I_{\text{DCO}}[k] \) (DCO mode)
Simulated Temperature Sensitivity

Free-running ring oscillator’s Temperature Coefficients (TC)

Nominal TC with different topologies:

- Constant-voltage bias (3700 ppm/°C)
- Constant-current bias (740 ppm/°C)
- CTAT-current bias (95 ppm/°C)

TC improvement: ↓5 × (constant I-bias) → ↓40 × (CTAT I-bias)

TC at corners with proposed topology:
Chip Micrograph

- CTAT Gen. Reference Ladder (0.4 μW)
- CTAT Gen. Opamp (2 μW)
- Pulse Gen. (12 μW)
- Ring DCO (91 μW)
Low TC DCO: Measurements

Temperature sensitivity over multiple chips (DCO tuned to 403 MHz at 25 °C)

F_{OSC} drift <4 MHz (401 to 405 MHz) across 0 to 55°C
Low TC DCO: Measurements

Measured distributions across 20 chips

Temperature coefficients over 0 to 55°C range

- Min: 113 ppm/°C
- Max: 157 ppm/°C

Avg. TC (20 chips) of 126 ppm/°C across 0 to 55°C
Low TC DCO: Measurements

Measured distributions across 20 chips
($\Delta F$: frequency deviation from nominal value at 25 °C)

Max frequency deviation over 0 to 55°C endpoints

Free-running oscillation frequencies

- $\mu = 1.47$ MHz
- $\sigma = 205$ kHz

- $\mu = 389$ MHz
- $\sigma = 12.5$ MHz
Low TC DCO: Measurements

Temperature sensitivity of same DCO tuned to different frequencies
(ΔF: frequency deviation from nominal value at 25 °C, \( F_0 \): Nominal tuned frequency)

Compensation consistent over multiple DCO modes
ILCM: Measured Output Spectrum

403 MHz MedRadio band carrier from 31 MHz reference
ILCM: Measured Phase Noise

-106.6 dBC/Hz phase noise at 300 kHz offset
ILCM: Measurements over 0 to 55°C

Worst case measured spectrum and phase noise over 0 to 55°C range

Carrier to spur ratio (CSR) > 20 dB

Phase Noise consistent
ILCM: Measured Power Start-up

Measured settling time with step voltage on the supply

Fast settling for duty-cycled operation
ILCM: Measured Lock Time

Measured settling time with reference injection kick-starting the oscillator:

\[ \approx 30 \text{ ns} \]

Period Jitter: \[ |T_{\text{measured}} - T_{\text{REF}}/N| \]

\[ \approx 150 \text{ ns (4 REF cycles) jitter settling} \]
## Low TC DCO: Standalone Performance

<table>
<thead>
<tr>
<th></th>
<th>[Zhang TCAS-I ‘11]</th>
<th>[Lee VLSIC ‘09]</th>
<th>[Lakhsmikumar CICC ‘07]</th>
<th>[Shrivastava CICC ‘12]</th>
<th>This Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>90 nm</td>
<td>180 nm</td>
<td>130 nm</td>
<td>130 nm</td>
<td>180 nm</td>
</tr>
<tr>
<td>Supply (V)</td>
<td>1</td>
<td>1.2</td>
<td>3.3</td>
<td>1.1</td>
<td>0.7</td>
</tr>
<tr>
<td>Frequency</td>
<td>1.8 GHz</td>
<td>10 MHz</td>
<td>1.25 GHz</td>
<td>100 kHz</td>
<td>400 MHz</td>
</tr>
<tr>
<td>TC (ppm/°C)</td>
<td>85</td>
<td>67</td>
<td>340</td>
<td>14</td>
<td>126 ¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>198 ²</td>
</tr>
<tr>
<td>Temp Range (°C)</td>
<td>7 to 62</td>
<td>-20 to 100</td>
<td>-40 to 120</td>
<td>20 to 70</td>
<td>0 to 55 ¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-40 to 100 ²</td>
</tr>
<tr>
<td># chips measured</td>
<td>1</td>
<td>–</td>
<td>15</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>$F_{osc}$ Tuning</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>✓ via DCO</td>
<td>✓ via DCO</td>
</tr>
<tr>
<td>Power</td>
<td>87 µW</td>
<td>80 µW</td>
<td>11 mW</td>
<td>1 µW</td>
<td>93 µW</td>
</tr>
</tbody>
</table>

1 – MedRadio temperature range; 2 – Full temperature range;

Low voltage, supports freq. tuning, supports injection-locking
# ILCM: Performance Summary

<table>
<thead>
<tr>
<th></th>
<th>[Li ISSCC ‘18]</th>
<th>[Liu JSSC ‘14]</th>
<th>[Pandey JSSC ‘11]</th>
<th>[Yang TBioCAS’13]</th>
<th>This Work</th>
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<tr>
<td>Tech.</td>
<td>65 nm</td>
<td>65 nm</td>
<td>90 nm</td>
<td>65 nm</td>
<td>180 nm</td>
</tr>
<tr>
<td>Supply (V)</td>
<td>1.1</td>
<td>0.8</td>
<td>0.7</td>
<td>1</td>
<td>0.7</td>
</tr>
<tr>
<td>Topology</td>
<td>ILRO</td>
<td>ILRO</td>
<td>ILRO</td>
<td>PLL</td>
<td>TC-ILRO</td>
</tr>
<tr>
<td></td>
<td>+ FTL</td>
<td>+ calibration</td>
<td>+EC</td>
<td>+ calibration</td>
<td></td>
</tr>
<tr>
<td>Freq. (MHz)</td>
<td>200</td>
<td>900</td>
<td>400</td>
<td>402</td>
<td>403</td>
</tr>
<tr>
<td>Multiplier</td>
<td>20 ×</td>
<td>9 ×</td>
<td>9 ×</td>
<td>1340 ×</td>
<td>13 ×</td>
</tr>
<tr>
<td>Phase noise</td>
<td>-95**</td>
<td>-100.8</td>
<td>-105.2</td>
<td>-102.1</td>
<td>-106.6</td>
</tr>
<tr>
<td>(dBc/Hz)</td>
<td>@300k</td>
<td>@1M</td>
<td>@300k</td>
<td>@200k</td>
<td>@300k</td>
</tr>
<tr>
<td>CSR (dB)</td>
<td>43</td>
<td>56#</td>
<td>44#</td>
<td>45</td>
<td>41#</td>
</tr>
<tr>
<td>Settling time</td>
<td>–</td>
<td>88 ns</td>
<td>250 ns</td>
<td>350 µs</td>
<td>30 ns</td>
</tr>
<tr>
<td>Lock time</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>150 ns</td>
</tr>
<tr>
<td>Power (µW)</td>
<td>130</td>
<td>538</td>
<td>&lt;90</td>
<td>430</td>
<td>107</td>
</tr>
<tr>
<td>PVT-robust?</td>
<td>P ✓ V ✓ T ✓</td>
<td>P ✓ V ✓ T x</td>
<td>P x V x T x</td>
<td>P ✓ V ✓ T ✓</td>
<td>P ✓ V ✓ T ✓</td>
</tr>
</tbody>
</table>

**From reported PN plot; #Nominal value at room/single temperature; *Across MedRadio temperature range (meeting 20 dB regulation)**
Conclusion

- Open-loop (PLL-free) ILCM
- Dynamic temperature variations addressed
- 126 ppm/°C Ring with minimal power overhead CTAT-biasing
- 150 ns start-up for duty-cycled operation
- Best combination of PVT-robustness & low power at comparable operation frequencies
Acknowledgement

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