Doherty-Chireix Continuum: Theory and Characterization

Patrick Roblin and Chenyu Liang

The Ohio State University
Outline

• PA Design at the CSRP and Embedding
• Dual-Input Theory at the CSRP
• Doherty Example
• Chireix Example
• Hybrid Chireix-Doherty PA
• Wideband Chireix to Doherty PA
• Summary
Bot processes enable to design PAs at the Current Source Reference Planes (CSRP)
Designing Dual-Input PAs at the Current Source Reference Planes (CSRP)

- First select the desired operating mode at the current source reference planes.

- Use embedding device model to get the waveforms at the package reference planes: provides multi-harmonic S-par. of the circuits needed.
Embedding Model in Verilog

Models Demoed:
- Angelov
- ASM-HEMT
- ANN

Embedding Model in Verilog:

\[
i_D = i_{Di} + \frac{dQ_D(v_{GSi}, v_{DSi})}{dt}
\]

\[
v_{DS} = v_{DSi} + i_D R_D
\]

\[
v_{GS} = v_{GSi}
\]
The **ANN device model** and the **ANN embedding device model** have the:

- Same Intrinsic load lines
- Same Extrinsic load lines
Automatic Design of Dual Input Doherty PA

Dr. Chenyu Liang, OSU

- Designed in 24 sec.
- Verified in 31 sec.

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Motivations for the Dual Input Architecture

• More degrees of freedom: 4 instead of 2
  – The phase difference between the two PA inputs: outphasing angle $\theta$
  – Different amplitudes for the two PA inputs

• Improve the average power efficiency
  – Better efficiency also means better thermal and thus improved reliability

• Simplified input matching design (no source pulling)
Dual Input Doherty PA Review

Doherty Goes Digital

Ramzi Darraj, Pedram Mousavi, and Fadhel M. Ghannouchi


Dual Input PAs at CSRP

Package Reference Planes (PRF)

Current Source Reference Planes (PRF)
Continuum Theory at CSRP (Fundamental)

Peak (p) and Backoff (b) Voltages and Currents:

\[ I_{mp} = |I_{mp}|, V_{mp} = |V_{mp}|, \]

\[ I_{mb} = |I_{mb}|, V_{mb} = |V_{mb}|, \]

\[ I_{ap} = |I_{ap}|e^{-j\theta_p}, V_{ap} = |V_{ap}|e^{-j\theta_p}, \]

\[ I_{ab} = |I_{ab}|e^{-j\theta_b}, V_{ab} = |V_{ab}|e^{-j\theta_b}. \]

Peak to Backoff Voltage and Current Ratios:

\[ |V_{mp}| = K_{vm}|V_{mb}|, \quad |V_{ap}| = K_{va}|V_{ab}|, \]

\[ |I_{mp}| = K_{im}|I_{mb}|, \quad |I_{ap}| = K_{ia}|I_{ab}|. \]

Use \( K_{vm} = 1 \) (\(|V_{mp}| = |V_{mb}|\)) for best backoff efficiency
Asymmetry Power Ratios

Reciprocity leads to:

$\theta_p + \theta_b = \pi$

$|V_{mb}||I_{mp}| - |V_{mp}||I_{mb}| = |V_{ab}||I_{ap}| - |V_{ap}||I_{ab}|$

Asymmetry power ratio between Aux and Main at peak power:

$n = \frac{P_{ap}}{P_{mp}} = \frac{|V_{ap}||I_{ap}|}{|V_{mp}||I_{mp}|} = \frac{1}{\gamma_{vp}\gamma_{ip}} = \frac{1/K_{im} - 1/K_{vm}}{1/K_{ia} - 1/K_{va}}$

Asymmetry power ratio between Aux and Main at backoff power:

$m = \frac{P_{ab}}{P_{mb}} = \frac{|V_{ab}||I_{ab}|}{|V_{mb}||I_{mb}|} = \frac{1}{\gamma_{vb}\gamma_{ib}} = \frac{K_{im} - K_{vm}}{K_{ia} - K_{va}}$

Output Backoff

$OBO = \frac{P_{o,peak}}{P_{o,back}} = K_{va}K_{ia} \frac{1 + \frac{1}{n}}{1 + \frac{1}{m}}$
Doherty-Chireix Continuum Theory

OBO=9=9.45 dB

Outphasing angles $\theta$ at backoff power within the continuum.

$$K_{va} = \frac{|V_{ap}|}{|V_{ab}|} \quad \text{and} \quad K_{ia} = \frac{|I_{ap}|}{|I_{ab}|}$$

$$\theta_b = \pm \cos^{-1} \left( \pm \sqrt{\frac{(K_{ia} - 1)(K_{im} - K_{va})}{(K_{im} + 1)(K_{ia} + K_{va})}} \right)$$

$$\theta_p = \pi - \theta_b.$$

Peak to backoff voltage ratio within the continuum.
Example of Dual-Input PAs with OBO B

<table>
<thead>
<tr>
<th>PA</th>
<th>$K_{vm}$</th>
<th>$K_{im}$</th>
<th>$K_{vu}$</th>
<th>$K_{ia}$</th>
<th>$\overline{P}_{o,\text{peak}}$</th>
<th>PBPR</th>
<th>$n$</th>
<th>$\theta_{b}$</th>
<th>$R_{mp}$</th>
<th>$R_{mb}$</th>
<th>$R_{ap}$</th>
<th>$R_{ab}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doherty</td>
<td>1</td>
<td>$\sqrt{B}/3$</td>
<td>$\sqrt{B}/3$</td>
<td>$\infty$</td>
<td>$B$</td>
<td>$\infty$</td>
<td>$\frac{0.5\sqrt{B}}{\sqrt{B-1}}$</td>
<td>$\frac{0.75}{2}$</td>
<td>$\sqrt{B} - 1$</td>
<td>$90^\circ$</td>
<td>$90^\circ$</td>
<td>$\sqrt{\frac{\gamma_{\text{up}}}{\gamma_{\text{ip}}} R_{\text{opt}}}$</td>
</tr>
<tr>
<td>Chireix</td>
<td>1</td>
<td>$B/9$</td>
<td>1</td>
<td>$B$</td>
<td>1</td>
<td>$B$</td>
<td>1</td>
<td>$\cos^{-1}\left(\pm \frac{B-1}{B+1}\right)$</td>
<td>$36.9^\circ$</td>
<td>$R_{\text{opt}}$</td>
<td>$B R_{\text{opt}}$</td>
<td>$R_{\text{opt}}$</td>
</tr>
<tr>
<td>Hybrid (HCD)</td>
<td>1</td>
<td>$B+1/2$</td>
<td>1</td>
<td>$B/9$</td>
<td>1</td>
<td>$B/9$</td>
<td>$\frac{B-1}{B+2}$</td>
<td>$\frac{B}{B+3}$</td>
<td>$\cos^{-1}\left(\pm \frac{B-1}{B+3}\right)$</td>
<td>$35.3^\circ$</td>
<td>$R_{\text{opt}}$</td>
<td>$\frac{B+1}{2} R_{\text{opt}}$</td>
</tr>
<tr>
<td>HD-max</td>
<td>1</td>
<td>$B/2$</td>
<td>$B/2$</td>
<td>1</td>
<td>$B$</td>
<td>1</td>
<td>$\cos^{-1}\left(\pm \sqrt{\frac{B^2-4B}{B^2-4}}\right)$</td>
<td>$40.1^\circ$</td>
<td>$R_{\text{opt}}$</td>
<td>$\frac{B}{2} R_{\text{opt}}$</td>
<td>$R_{\text{opt}}$</td>
<td>$\infty$</td>
</tr>
</tbody>
</table>
Peak Power for Devices with Same Periphery

OBO=9=9.45 dB

\[ K_{va} = \frac{|V_{ap}|}{|V_{ab}|} \quad \text{and} \quad K_{ia} = \frac{|I_{ap}|}{|I_{ab}|} \]

\[ P_{o,peak} = \frac{P_{o,peak}}{2P_{max}(n)} = \begin{cases} \frac{1}{2} (1 + \frac{1}{n}) & n \geq 1 \\ \frac{1}{2} (1 + n) & n < 1, \end{cases} \]

where \( P_{max}(n) \) is the power of the device (main or auxiliary) providing the most power.
Combiner Realization for $\gamma_{vp} = 1$ ($|V_{ap}| = |V_{mp}|$)

Realization using transmission lines (TL)

$Z_1 = R_{mp}$

$Z_2 = R_{ap}$

$R_L = \frac{R_{mp}}{n + 1}$

$\tan \theta_1 = \frac{K_{im}(K_{ia} - 1)}{K_{ia} + K_{im}} \tan \theta_b$

$\tan \theta_2 = \frac{K_{ia}(K_{va} - K_{im})}{K_{va}(K_{ia} + K_{im})} \tan \theta_b$
Broadband Performance of TL Combiner

Impedance match at peak power is freq. independent

PA is broadband at peak power!

Outphasing Angles:
\[ \theta_p(\omega) = \theta_1(\omega) - \theta_2(\omega) \]
\[ \theta_b(\omega) = \pi - \theta_p(\omega) \]

Linear TL dispersion
\[ \theta_i(\omega) = \theta_i(\omega_0) \frac{\omega}{\omega_0} \]
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Generalized Doherty PA Design

\[ |V_{mb}| = -jZ_T |I_{ab}| + |I_{mb}| \frac{Z_T^2}{R_L}, \]

\[ |V_{mp}| = -jZ_T |I_{ap}| + |I_{mp}| \frac{Z_T^2}{R_L}. \]

Design Equations Accounting for Auxiliary not fully Off at Backoff

\[ Z_T = \frac{|V_{mb}||I_{mp}| - |V_{mp}||I_{mb}|}{|I_{mb}||I_{ap}| - |I_{mp}||I_{ab}|}, \]

\[ R_L = \frac{(|V_{mb}||I_{mp}| - |V_{mp}||I_{mb}|)^2}{(|I_{mb}||I_{ap}| - |I_{mp}||I_{ab}|)(|V_{mb}||I_{ap}| - |V_{mp}||I_{ab}|)}. \]

\[ \text{OBO} = K_{vm}^2 = \left( \frac{K_{vm}(n + 1)}{1 + n \frac{K_{vm}}{K_{ia}}} \right)^2 \]
GUI For Automatic PA Design (Matlab/ADS)

<table>
<thead>
<tr>
<th>Input Variables for Main (m) and Aux. (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>V_{max}</td>
</tr>
<tr>
<td>Gamma_{m}</td>
</tr>
<tr>
<td>VGS_{DC,m-MTH}</td>
</tr>
<tr>
<td>VGS_{DC,a}</td>
</tr>
<tr>
<td>Doherty Tuning Factor</td>
</tr>
<tr>
<td>VGS _MAX</td>
</tr>
<tr>
<td>VGS _MIN</td>
</tr>
<tr>
<td>VGS_{ap} _MAX</td>
</tr>
<tr>
<td>VGS_{ap} _MIN</td>
</tr>
<tr>
<td>Co-Design</td>
</tr>
<tr>
<td>Verification</td>
</tr>
</tbody>
</table>

Output for DPA Prototype

| R_L | 20.3279 Ohm |
| Z_T | 31.5939 Ohm |
| VGS_{mb} | 0.8910 V |
| VGS_{mo} | 2.5728 V |
| VGS_{ab} | 1.0418 V |
| VGS_{ap} | 3.8692 V |

Case I

Case II

Case Clear

Case Quit
Doherty PA Example
LTG results for Dual Input Doherty PA

Dr. Chenyu Liang, OSU

LTE results for Dual Input Doherty PA

<table>
<thead>
<tr>
<th>Signal</th>
<th>Output PAPR (dB)</th>
<th>$P_{inc,avg.}$ (dBm)</th>
<th>$P_{out,avg.}$ (dBm)</th>
<th>$P_{out,peak}$ (dBm)</th>
<th>Gain$_{avg.}$ (dB)</th>
<th>$\eta_{DE,avg.}/P_{AE,avg.}$ (%)</th>
<th>ACLR$_{L,H}$ (dBc)</th>
<th>NMSE (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before DPD 10 MHz LTE</td>
<td>9.47</td>
<td>18.3, 13.2</td>
<td>33.9</td>
<td>43.4</td>
<td>14.4</td>
<td>55.2/53.2</td>
<td>−28.1, −28.9</td>
<td>−19.2</td>
</tr>
<tr>
<td>After DPD 10 MHz LTE</td>
<td>9.50</td>
<td>17.9, 13.8</td>
<td>33.8</td>
<td>43.4</td>
<td>14.5</td>
<td>53.4/51.4</td>
<td>−49.8, −48.9</td>
<td>−33.4</td>
</tr>
<tr>
<td>Before DPD 20 MHz LTE</td>
<td>9.28</td>
<td>17.4, 13.2</td>
<td>33.5</td>
<td>42.8</td>
<td>14.7</td>
<td>54.1/52.2</td>
<td>−28.5, −30.2</td>
<td>−18.1</td>
</tr>
<tr>
<td>After DPD 20 MHz LTE</td>
<td>9.40</td>
<td>17.6, 12.8</td>
<td>33.8</td>
<td>43.2</td>
<td>14.4</td>
<td>53.3/51.6</td>
<td>−47.1, −45.6</td>
<td>−32.7</td>
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Chireix Design Example using Class F

\[ V_{DD} \]

\[ I_{D1}(v_{GS}, v_{DS}) \]

\[ 2\omega \]

**Intrinsic Drain**

Ideal Triplexer (no phase delay)

Lossless Combiner Network Loaded with \( R_L \)

**Intrinsic Drain**

Sub-Circuit 1

\[ I_{L1}(\omega)I_{L2}(\omega) \]

\[ R_L \]

\[ \theta_B = \pm \cos^{-1} \left( \pm \frac{R_{max} - R_{min}}{R_{max} + R_{min}} \right) \]

\[ \theta_P = \pi - \theta_B \]
Peak and Backoff Selection

Selected R\text{max} and R\text{min} and RF drives given desired OBO and optimal η using a single transistor simulation.

\begin{itemize}
  \item RF drive scanning
  \item OBO
\end{itemize}

\begin{itemize}
  \item R\text{max} = 200Ω
  \item 1.7 V
  \item 0.9 V
  \item 2.3 V
  \item 1.1 V
\end{itemize}
CW Measurement of Chireix PA

Mixed mode operation for optimal backoff operation

<table>
<thead>
<tr>
<th>$f_o$ (GHz)</th>
<th>Signal</th>
<th>PAPR (dB)</th>
<th>$P_{inc,avg}$ (dBm)</th>
<th>$P_{o,avg}$ (dBm)</th>
<th>Gain (dB)</th>
<th>$\eta_{DE,avg}$ (%)</th>
<th>ACLR$_1$ (dBc)</th>
<th>NMSE (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before DPD</td>
<td>1.9 3.84 MHz WCDMA</td>
<td>9.57</td>
<td>17.17, 19.14</td>
<td>34.46</td>
<td>13.18</td>
<td>59.5</td>
<td>-27.7, -27.51</td>
<td>-18.88</td>
</tr>
<tr>
<td>After DPD</td>
<td>1.9 3.84 MHz WCDMA</td>
<td>9.51</td>
<td>17.6, 19.3</td>
<td>34.5</td>
<td>12.95</td>
<td>59.5</td>
<td>-50.96, -51.48</td>
<td>-38.53</td>
</tr>
<tr>
<td>Before DPD</td>
<td>1.9 10 MHz LTE</td>
<td>9.64</td>
<td>17.01, 18.09</td>
<td>34.43</td>
<td>13.33</td>
<td>59.32</td>
<td>-27.69, -29.42</td>
<td>-18.82</td>
</tr>
<tr>
<td>After DPD</td>
<td>1.9 10 MHz LTE</td>
<td>9.6</td>
<td>17.44, 19.3</td>
<td>34.46</td>
<td>13</td>
<td>59.4</td>
<td>-45.33, -46.4</td>
<td>-33.92</td>
</tr>
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2 GHz HCD PA ($K_{v\alpha} = 1$)

Simulated intrinsic efficiency and outphasing angles.
Optimal drain efficiency, PAE and outphasing angles.

Comparison between HCD ($K_{va} = 1$) and Doherty ($K_{va} = 3$) PA at 2 GHz
HCD Performance for LTE Signals

Power Spectrum density before and after DPD

AM/AM before and after DPD

AM/PM before and after DPD.

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<thead>
<tr>
<th>Signal</th>
<th>PAPR (dB)</th>
<th>$P_{inc,avg.}$ (dBm)</th>
<th>$P_{out,avg.}$ (dBm)</th>
<th>$P_{out,peak}$ (dBm)</th>
<th>$\eta_{D,avg.}/PAE_{avg.}$ (%)</th>
<th>$ACLR_{L,H}$ (dBc)</th>
<th>NMSE (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before DPD 10 MHz LTE</td>
<td>8.4</td>
<td>22.7, 21.7</td>
<td>34.4</td>
<td>42.8</td>
<td>63.0/55.4</td>
<td>-30.7, -30.0</td>
<td>-15.2</td>
</tr>
<tr>
<td>After DPD 10 MHz LTE</td>
<td>9.6</td>
<td>21.2, 20.3</td>
<td>33.3</td>
<td>42.9</td>
<td>60.3/53.4</td>
<td>-53.2, -51.2</td>
<td>-35.4</td>
</tr>
<tr>
<td>Before DPD 20 MHz LTE</td>
<td>8.5</td>
<td>22.7, 21.7</td>
<td>34.4</td>
<td>42.9</td>
<td>62.3/54.9</td>
<td>-31.7, -30.5</td>
<td>-15.8</td>
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<td>After DPD 20 MHz LTE</td>
<td>9.4</td>
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Simulated wideband drain efficiency at CSRP

Simulated load modulation trajectories for the main PA.

Simulated load modulation trajectories for the auxiliary PA.
Measured Broadband Performance

Comparison between ADS simulation and CW measurements

Efficiency versus Frequency

Small-signal S-par.
20 MHz LTE at 1.7, 2.2 and 2.5 GHz

Output power spectra density

AM/AM and AM/PM
Wideband Hybrid Doherty Outphasing PA

Dr. Chenyu Liang, OSU Alum

Modulated Signal Measurement With 20 MHz LTE Signal

<table>
<thead>
<tr>
<th></th>
<th>$f_0$ (GHz)</th>
<th>Output PAPR (dB)</th>
<th>$P_{\text{inc.,avg.}}$ (dBm)</th>
<th>$P_{\text{out.,avg.}}$ (dBm)</th>
<th>Gain$_{\text{avg}}$ (dB)</th>
<th>$\eta_{\text{DE,,avg.}}$ / $\text{PAE}_{\text{avg.}}$ (%)</th>
<th>ACLR$_{L,H}$ (dBc)</th>
<th>NMSE (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before DPD</td>
<td>1.7</td>
<td>6.9</td>
<td>25.3</td>
<td>37.2</td>
<td>11.9</td>
<td>50.3 / 47.1</td>
<td>-32.4, -31.8</td>
<td>-20.5</td>
</tr>
<tr>
<td>After DPD</td>
<td>1.7</td>
<td>6.4</td>
<td>25.3</td>
<td>37.7</td>
<td>12.4</td>
<td>47.8 / 45.0</td>
<td>-54.0, -52.3</td>
<td>-42.9</td>
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<tr>
<td>Before DPD</td>
<td>2.2</td>
<td>8.0</td>
<td>24.3</td>
<td>35.2</td>
<td>10.9</td>
<td>40.0 / 36.7</td>
<td>-30.2, -30.5</td>
<td>-14.7</td>
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<td>35.5</td>
<td>8.0</td>
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</tr>
<tr>
<td>After DPD</td>
<td>2.5</td>
<td>6.2</td>
<td>28.4</td>
<td>35.4</td>
<td>7.0</td>
<td>40.4 / 32.3</td>
<td>-47.6, -49.2</td>
<td>-33.8</td>
</tr>
</tbody>
</table>
Dual Input PAs from the Ohio State U.

Dr. Hsiu-Chen Chang
OSU Alum

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OSU Alum
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Summary

• Dual Input PA provides more degrees of freedom in design
• Dual-Input PAs benefit from being designed at the CSRP
• Embedding or Deembedding make PA design at the CSRP possible
• A continuum of high efficiency operation is available for dual-input PAs at the CSRP
• New high performance mode discovered (HCD and HDmax)
• Broadband Design is possible using sliding mode concept
Dual Input PAs from the Ohio State U.


