Design of Linear CMOS
RF Power Amplifiers

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Outline

- Introduction
- Linear Power Amplifier (PA) basics
- Efficiency enhancement: Dynamic Supply
- Conclusion
Introduction

RF Applications
RF Transceiver

Direct conversion transmitter
Two-port representation / S-parameters

**Admittance**

\[ I_1 = y_{11} \cdot V_1 + y_{12} \cdot V_2 \]
\[ I_2 = y_{21} \cdot V_1 + y_{22} \cdot V_2 \]

\[ y_{11} = \left. \frac{I_1}{V_1} \right|_{V_2 = 0} \]
\[ y_{12} = \left. \frac{I_1}{V_2} \right|_{V_1 = 0} \]
\[ y_{21} = \left. \frac{I_2}{V_1} \right|_{V_2 = 0} \]
\[ y_{22} = \left. \frac{I_2}{V_2} \right|_{V_1 = 0} \]

\[ V_1 = z_{11} \cdot I_1 + z_{12} \cdot I_2 \]
\[ V_2 = z_{21} \cdot I_1 + z_{22} \cdot I_2 \]

\[ z_{11} = \left. \frac{V_1}{I_1} \right|_{I_2 = 0} \]
\[ z_{12} = \left. \frac{V_1}{I_2} \right|_{I_1 = 0} \]
\[ z_{21} = \left. \frac{V_2}{I_1} \right|_{I_2 = 0} \]
\[ z_{22} = \left. \frac{V_2}{I_2} \right|_{I_1 = 0} \]

**Impedance**

\[ V_1 = z_{11} \cdot I_1 + z_{12} \cdot I_2 \]
\[ V_2 = z_{21} \cdot I_1 + z_{22} \cdot I_2 \]

\[ z_{11} = \left. \frac{V_1}{I_1} \right|_{I_2 = 0} \]
\[ z_{12} = \left. \frac{V_1}{I_2} \right|_{I_1 = 0} \]
\[ z_{21} = \left. \frac{V_2}{I_1} \right|_{I_2 = 0} \]
\[ z_{22} = \left. \frac{V_2}{I_2} \right|_{I_1 = 0} \]

**Scattering**

\[ b_1 = s_{11} \cdot a_1 + s_{12} \cdot a_2 \]
\[ b_2 = s_{21} \cdot a_1 + s_{22} \cdot b_2 \]

\[ s_{11} = \left. \frac{b_1}{a_1} \right|_{a_2 = 0} \]
\[ s_{12} = \left. \frac{b_1}{a_2} \right|_{a_1 = 0} \]
\[ s_{21} = \left. \frac{b_2}{a_1} \right|_{a_2 = 0} \]
\[ s_{22} = \left. \frac{b_2}{a_2} \right|_{a_1 = 0} \]

S-parameters are easier to measure. No need of neither short nor open circuits.
PA Classes

- Linear classes: A, AB, B et C
  - some details
- Non linear: D, E et F
  - out of the scope
Linear classes

Conduction angle $\alpha$ decreases

From Schlumpf [1]
Linear classes - comparison

Weak-strong non-linear model*

Gain linearity*

*From Cripps [2]
Class choice according to application

- Constant envelope modulation (GSM):
  - high efficiency PA (switched PA classes)
  - linearity not important

- Variable envelope modulation (IS-95, UMTS, WLAN):
  - linearity very important
    - Linear PA + efficiency enhancement technique
    - high efficiency PA + linearization technique
WLAN 802.11a/g

- Enveloppe variable
- large PAPR (17dB, $\sqrt{52}$)
- Requires a high linearity PA

Class A PA
Class A PA

Drain voltage

Drain current

\[ m2 = (V_{knee}, I_{max}) \]
\[ m4 = (V_{br}, I_{min}) \]
\[ m5 = (V_{dc}, I_{dc}) \]
Class A PA – Output Power I

If output voltage and \( R_{OPT} \) are known:

\[
V_{DC} = \frac{1}{2} (V_{BR} + V_{KNEE}) \quad I_{DC} = \frac{1}{2} I_{MAX}
\]

\[
P_{OUT\_MAX} = \frac{V_{eff}^2}{R_{OPT}} \quad V_{eff} = \frac{V_{PP}}{2 \cdot \sqrt{2}}
\]

\[
\begin{align*}
P_{OUT\_MAX} &= \frac{\left(\frac{V_{PP}}{2 \cdot \sqrt{2}}\right)^2}{R_{OPT}} = \frac{V_{PP}^2}{8 \cdot R_{OPT}} \\
V_{PP} &= V_{BR} - V_{KNEE}
\end{align*}
\]

If current and \( R_{OPT} \) are known:

\[
P_{OUT\_MAX} = R_{OPT} \cdot I_{eff}^2 \quad I_{eff} = \frac{I_{MAX}}{2 \cdot \sqrt{2}}
\]

\[
P_{OUT\_MAX} = R_{OPT} \cdot \left(\frac{I_{MAX}}{2 \cdot \sqrt{2}}\right)^2 = R_{OPT} \cdot \frac{I_{MAX}^2}{8}
\]

\[
P_{OUT\_MAX} = \frac{1}{8} \cdot \frac{(V_{BR} - V_{KNEE})^2}{R_{OPT}}
\]
Class A PA – Output power II

If output voltage and current are known:

\[ P_{OUT\_MAX} = V_{eff} \cdot I_{eff} \]

\[ V_{eff} = \frac{V_{PP}}{2 \cdot \sqrt{2}} \]

\[ I_{eff} = \frac{I_{MAX}}{2 \cdot \sqrt{2}} \]

\[ P_{OUT\_MAX} = \frac{V_{PP}}{2 \cdot \sqrt{2}} \cdot \frac{I_{MAX}}{2 \cdot \sqrt{2}} = \frac{V_{PP} \cdot I_{MAX}}{8} \]

\[ P_{OUT\_MAX} = \frac{1}{8} \cdot (V_{BR} - V_{KNEE}) \cdot I_{MAX} \]

\[ P_{OUT\_MAX} = \frac{1}{4} (V_{BR} - V_{KNEE}) \cdot I_{DC} \]

\[ P_{OUT\_MAX} = \frac{1}{4} (V_{DC} - V_{KNEE}) \cdot I_{MAX} \]

\[ P_{OUT\_MAX} = \frac{1}{2} (V_{DC} - V_{KNEE}) \cdot I_{DC} \]

Expressions for \( R_{OPT} \):

\[ R_{OPT} = \frac{(V_{DC} - V_{KNEE})}{I_{DC}} \]

\[ R_{OPT} = \frac{(V_{DC} - V_{KNEE})^2}{2 \cdot P_{OUT\_MAX}} \]

\[ R_{OPT} = \frac{V_{BR} - V_{KNEE}}{I_{MAX}} \]

\[ R_{OPT} = \frac{1}{8} \cdot \frac{(V_{BR} - V_{KNEE})^2}{P_{OUT\_MAX}} \]
Considerations on $R_{OPT}$

- It is necessary to guarantee that the desired maximum output power can be delivered to the load:
  - limited supply voltage
  - transistor non idealities
Transistor sizing

For a given output power, if \( V_{BR} \) and \( V_{KNEE} \) of the transistor are known:

1. Determine \( R_{opt} \)

\( R_{OPT} = \frac{1}{8} \frac{(V_{BR} - V_{KNEE})^2}{P_{OUT\_MAX}} \)

2. Calculate necessary \( I_{MAX} \)

\( I_{MAX} = \frac{(V_{BR} - V_{KNEE})}{R_{OPT}} \)

3. The transistor must be designed for \( I_{MAX} \)

\( I_D = \frac{1}{2} k' \frac{W}{L} (V_{GS} - V_T)^2 \)

4. Calculate \( W/L \)

\( \frac{W}{L} = \frac{2 \cdot I_{MAX}}{k' \cdot (V_{GS} - V_T)^2} \)

5. Verification with simulator
Choice of VGS and W/L

• Case 1 – integrated transceiver
  – input capacitance
  – input signal swing

• Case 2 – stand-alone PA
  – No constraints, VGS and W/L can be chosen so as to maximize linearity or efficiency
**PA stability**

**K factor > 1 (Rollet [3])**

\[
K = \frac{1 + |D|^2 - |s_{11}|^2 - |s_{22}|^2}{2|s_{12}s_{21}|}
\]

\[
D = s_{11}s_{22} - s_{12}s_{21}
\]

**B1 > 0 (Bodway [3])**

\[
B_1 = 1 + |s_{11}|^2 - |s_{22}|^2 - |D|^2
\]
Stabilized PA

- Input Matching
- Output Matching
- RF Choke
- DC Block
- V_{supply}
- V_{in}
- V_{bias}
- R_{bias}
- R_{stab1}
- R_{stab2}
- C_{stab}
Impedance matching networks

- For the determined $R_{\text{OPT}}$, find correspondent \( \Gamma_{IN} \) and choose \( \Gamma_S = \Gamma_{IN}^* \)

- Choose a matching network for the output, in general low-pass (to attenuate harmonics), to transform the antenna impedance into $R_{\text{OPT}}$ (Smith Chart [4])

- Choose a convenient matching network for the input so that the desired matching can be attained
Linearity I – 2-tone

1-dB Compression Point

\[ 20 \log A_{out} \]

\[ A_{1\text{-dB}} \]

\[ 20 \log A_{in} \]

\[ 1 \text{ dB} \]

\[ f_1 \]

\[ f_2 \]

\[ 2f_1 - f_2, f_1, f_2, 2f_2 - f_1 \]

\[ \text{Input} \]

\[ \text{Output} \]

3rd Order Intermodulation Distortion (IMD3)

3rd Order Intercept Point

Interferers

Desired Channel

Amplifier

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Linearity II - OFDM

IEEE802.11a – EVM < -25dB (5.6%)
OFDM, 64QAM, 54Mbps
In general, EVM < 3%
Efficiency

Class A PA:
- Max efficiency with $P_{\text{OUT_MAX}}$
- Consumes power even without input signal
- Efficiency depends also on gain

$PAE = \frac{P_{\text{OUT}} - P_{\text{IN}}}{P_{\text{DC}}}$

$\eta = \frac{P_{\text{OUT}}}{P_{\text{DC}}}$

$P_{\text{OUT}} = G \cdot P_{\text{IN}}$

$PAE = \eta_D \cdot \left(1 - \frac{1}{G}\right)$
Scenario

- Mobile devices require high efficiency circuits
- Applications such as WLAN (variable envelope) requires high linearity PAs
- RF power amplifiers are power hungry devices
- High efficiency PA means low linearity PA
Improving efficiency...

\[ PAE = \frac{P_{OUT} - P_{IN}}{P_{DC}} \]

\[ P_{DC} = V_{DD} \cdot I_{DD} \]
What if …?
What if....?

\[ PAE = \frac{P_{OUT} - P_{IN}}{P_{DC}} \]

\[ P_{DC} = V_{DD} \cdot I_{DD} \]

Low output power: \( V_{DC} \downarrow \)

High output power: \( V_{DC} \uparrow \)

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Dynamic Supply

From Crippps, Microwave Magazine Oct-2010
Articles about enhancement techniques

- Dynamic Supply:
  - Hanington [5], 1999 (T-MTT)
  - Schlumpf [1], 2004 (JSSC)
  - Minnis [7], 2009 (T-CAS-1)
  - Larson [10], 2008 (CICC)
  - Jeong [9], 2009 (T-MTT)

- EER:
  - Chen [6], 2004 (MTT-S)
Envelope processing

\[ V_{\text{supply}} \]

\[ V_{s4} \quad G_{\text{env}} \quad V_{s1} \]

\[ V_{\text{env}} \]

Gain

Dynamic Supply

\[ V_s(P_{\text{in}}) \]

\[ V_{s4} \quad V_{s3} \quad V_{s2} \quad V_{s1} \]

\[ P_{\text{in}} \]

\[ G_{\text{env}} \cdot |V_{\text{in}}| + V_{\text{knee}} < V_{s1} \quad \rightarrow \quad V_s(P_{\text{in}}) = V_{s1} \]

\[ V_{s1} \leq G_{\text{env}} \cdot |V_{\text{in}}| + V_{\text{knee}} \leq V_{s4} \quad \rightarrow \quad V_s(P_{\text{in}}) = G_{\text{env}} \cdot |V_{\text{in}}| + V_{\text{knee}} \]

\[ G_{\text{env}} \cdot |V_{\text{in}}| + V_{\text{knee}} \geq V_{s4} \quad \rightarrow \quad V_s(P_{\text{in}}) = V_{s4} \]
High-Efficiency Modulator

\[ \eta = 86\% \]

\[ f_s \cdot t_d \cdot 360^\circ + \varphi_{LC}(f_s) = 180^\circ \]

\[ t_d = 4.5\text{ns} \]

\[ f_s = 110\text{MHz} \]

fully differential comparator

anti overlapping circuit

\[ \text{VDD} \]

\[ \text{L}_{\text{filter}} \]

\[ V_{\text{supply}} \]

\[ R_{\text{PA}} \]

\[ C_{\text{filter}} \]
fully differential comparator

anti overlapping circuit

VDD

L_{filter}

out

V_{supply}

C_{filter}

R_{PA}
High-Speed Comparator
The RF Power Amplifier

Input Matching

Output Matching

RF Choke

V_{supply}

86mA

672
0.24

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Measurements I
Measurements II
Measurement Results [8]

1.35 mm²
Gain vs. Input Power 2.4GHz

- 2.5V
- 2.0V
- Dynamic
- 1.5V
- 1.0V

Gain (dB)

Input Power (dBm)

Gain vs. Input Power 2.4GHz

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Efficiency vs. Output Power 2.4GHz

Output Power (dBm) vs. PAE (%) for 2.4GHz RF transmitter.

- **Dyn**: Dynamic mode efficiency curve.
- **Cst**: Constant mode efficiency curve.
- **Ratio**: Efficiency ratio curve.

Key points:
- Efficiency peaks at around 5% for both Dyn and Cst modes.
- Efficiency decreases as output power increases beyond certain levels.

Additional notes:
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EVM vs. Efficiency 2.4GHz

- Dynamic
- Constant
- Limit

6.6 8.2

1.6%

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Summary & Conclusion

- RF power amplifier basics
- Dynamic supply principle
- Modulator and PA circuits
- Improvement needed for WLAN application
- Efficiency enhancement verified through measurement results at 2.4 and 5.2GHz
References

[2] Steve C. Cripps, RF PAs for Wireless Communications
[3] G. Gonzalez, Microwave Transistor Amplifiers