RF Power Amplifier Design

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Efficiency Definitions

- Drain Efficiency: \( \eta_D = \frac{P_{OUT}}{P_{DC}} \)

- Power Added Efficiency: \( \eta_{PA} = \frac{P_{OUT} - P_{IN}}{P_{DC}} = \eta_D \cdot \left(1 - \frac{1}{G}\right) \)

Ideal FET Input and Output Characteristics

\[ g_m = \begin{cases} \frac{V_{DS}}{V_{DS}} & \text{Ohmic} \\ \frac{V_{DS}}{V_{DS}} & \text{Saturation} \\ \frac{V_{DS}}{V_{DS}} & \text{Breakdown} \end{cases} \]

\[ k = \frac{V_{DD} - V_K}{V_{DD}} \]
Maximum Output Power Match

\[ R_{OPT} = \frac{V_{DS \max} - V_K}{I_m} \]
Class A – Circuit

\[ V_{DD} \]
\[ G \]
\[ B \]
\[ R_L \]
\[ S \]

\[ \eta_d = \kappa \cdot 50\% \]

\[ G = G_A \quad \text{(e.g. 14 dB)} \]

\[ \eta_{PA} = \kappa \cdot 48\% \]

Class B

\[ I_{os} \]
\[ I_m \]
\[ I_{os} \]

\[ V_{os} \]
\[ V_X \]
\[ V_{DD} \]
\[ V_{DSmax} \]

\[ V_{os} \]
\[ V_{DD} \]
\[ V_{DS} \]

\[ V_{os} \]
\[ V_{DS} \]

\[ I_{os} \]
\[ I_m \]

\[ V_{os} \]
\[ V_{DD} \]
\[ V_{DS} \]
Class C

Class B and C – Circuit

Class B
\[ \eta_B = \kappa \cdot 78\% \]
\[ G = G_A - 6\text{dB} \quad (8 \text{ dB}) \]
\[ \eta_{PA} = \kappa \cdot 65\% \]

Class C
\[ \eta_C \to 100\% \]
\[ G \to 1 \]
\[ \eta_{PA} \to 0\% \]
Influence of Conduction Angle

Class F (HCA ... harmonic controlled amplifier)
**hHCA (half sinusoidally driven HCA)**

![Diagram of hHCA](image)

**Class F and hHCA – Circuit**

- **Class F**
  - $\eta_d = \kappa \cdot 100\%$
  - $G = G_a - 5\text{dB} \quad (9\text{ dB})$
  - $\eta_{PA} = \kappa \cdot 87\%$

- **hHCA**
  - $\eta_d = \kappa \cdot 100\%$
  - $G = G_a + 1\text{dB} \quad (15\text{ dB})$
  - $\eta_{PA} = \kappa \cdot 96\%$
**hHCA – Third Harmonic Peaking**

- **I_{os}**
- **I_{m}**
- **V_{DD}**
- **V_{DSmax}**
- **V_{GS}**
- **V_{DS}**
- **2V_{P}**
- **V_{P}**
- **0**
- **V_{os}**
- **p**
- **2p**
- **Q**

**Third Harmonic Peaking – Circuit**

\[ \eta_D = \kappa \cdot 91\% \]

\[ G = G_A + 0.6\text{dB} \quad (14.6\text{ dB}) \]

\[ \eta_{PA} = \kappa \cdot 87\% \]
Linearity Aspects

- Class A
- Class B
- Class AB
- Class C
Linearity Aspects

- Ideal strongly nonlinear model
- Strong-weak nonlinear model

Amplifier Design – An Example

- Balanced Amplifier Configuration
Amplifier Design – Simulation

- Gate & Drain Waveforms

Amplifier Design – Simulation

- Dynamic Load Line & Power Sweep
Amplifier Design – Measurements

- Single Tone & Two Tone

Amplifier Nonlinearity

- Gain and Phase depends on Input Signal
- 3rd Order Gain-Nonlinearities:
Amplifier Nonlinearity

- Higher Output Level (close to Saturation) results in more Distortion/Nonlinearity

Nonlinearity leads to?

- Generation of Harmonics
- Intermodulation Distortion / Spectral Regrowth
- SNR (NPR) Degradation
- Constellation Deformation
Intermodulation and Harmonics

Energy in adjacent Channels
ACPR (Adjacent Channel Leakage Power Ratio) increases
**Reduced NPR (Noise Power Ratio)**

- **Input Signal**
- **Output Signal of Nonlinear Amplifier**

  Degradation of Inband SNR
  „Noisy“ Constellation

**Constellation Deformation**

- **Input Signal**
- **Output Signal of Nonlinear Amplifier (with Gain- and Phase-Distortion)**
Modeling of Nonlinearities

- with Memory-Effects
  - Volterra Series (= "Taylor Series with Memory")

- without Memory-Effects
  - Saleh Model \( f(r) = \frac{\alpha_r r}{1 + \beta_r r^2} \)
  - Taylor Series
  - Blum and Jeruchim Model
  - AM/AM- and AM/PM-conversion

AM/AM- and AM/PM-Conversion

- GaAs-PA

![Graphs of AM/AM- and AM/PM-Conversion]
AM/AM- and AM/PM-Conversion

- LDMOS-PA

How to preserve Linearity?

- Backed-Off Operation of PA
  - Simplest Way to achieve Linearity

- Linearity improving Concepts
  - Predistortion
  - Feedforward
  - ...

How to preserve Efficiency?

- Efficiency improving Concepts
  - Doherty
  - Envelope Elimination and Restoration
  - ...

- Linearity improving Concepts
  - Higher Linearity at constant Efficiency
  - Higher Efficiency at constant Linearity

Direct (RF) Feedback

- Classical Method
- Decrease of Gain \(\rightarrow\) Low Efficiency
- Feedback needs more Bandwidth than Signal
- Stability Problems at high Bandwidths
**Distortion Feedback**

- Feedback of outband Products only
- Higher Gain than RF feedback
- Stability Problems due to Reverse Loop

**Feedforward**

- Overcomes Stability Problem by forward-only Loops
- Critical to Gain/Phase-Imbalances
  - 0.5dB Gain Error → -31dB Cancellation
  - 2.5° Phase Error → -27dB Cancellation
- Well suited for narrowband application
Cartesian Feedback

- AM/AM- and AM/PM-correction
- High Feedback-Bandwidth
- Stability Problems

Digital Predistortion

- Digital Implementation of „Cartesian Feedback“
- Additional ADCs, DSP Power, Oversampling needed
- Loop can be opened \(\rightarrow\) no Stability Problems
Analog Predistortion

- Predistorter has inverse Function of Amplifier
- Leads to infinite Bandwidth (!)
- Hard to realize (accuracy)

Possible Realizations:
LINC (Linear Amplification by Nonlinear Components)

- AM/AM- and AM/PM-correction
- Digital separation required (accuracy!)
- High Bandwidth, oversampling necessary
- Stability guaranteed

\[ s(t) \rightarrow Ks(t) \rightarrow s(t) \]

UMTS example:

\[
\begin{align*}
\text{ACPR}_1 &= 60\,\text{dB} \\
\text{ACPR}_2 &= 60\,\text{dB} \\
\text{ACPR}_1 &= 18\,\text{dB} \\
\text{ACPR}_2 &= 29\,\text{dB}
\end{align*}
\]

Doherty Amplifier

- Auxiliary amplifier supports main amplifier during saturation
- PAE can be kept high over a 6dB range
Doherty Amplifier

- Gain vs. Input Power
- Efficiency vs. Input Power
- No improvement of AM/AM- and AM/PM-distortion
- Behavior of auxiliary amplifier very hard (impossible) to realize
- Stability guaranteed

EER (Envelope Elimination and Restoration)

- Separating phase and magnitude information
- Elimination of AM/AM-distortion
- Application of high-efficient amplifiers (independent of amplitude distortion)
- Stability guaranteed
EER (Envelope Elimination and Restoration)

- **Analog realization**
  - Limiter hard to build
  - Accuracy problems
  - Feedback necessary

- **Digital realization**
  - Oversampling + high D/A-conversion rates required
  - High power consumption of DSP and D/A-converters
  - Possible feedback elimination
  - Compensation of AM/PM-distortion possible

### EER (Envelope Elimination and Restoration)

- Bandwidth of Magnitude- and phase-signal have higher than transmit signal
- Five times (!) oversampling necessary to achieve standard requirements

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**UMTS example:**

- ACPR = 60 dB
- ACPR = 40 dB
- ACPR = 30 dB
- ACPR = 20 dB
- ACPR = 10 dB
- ACPR = 0 dB
- ACPR = -10 dB
- ACPR = -20 dB
- ACPR = -30 dB
- ACPR = -40 dB

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**RF input**

- Supply voltage amplifier
- Peak detector
- Limiter

**RF output**

- Supply voltage amplifier
- Peak detector
- Limiter

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**Digital signal processor**

- I
- Q
- Modulator
- Local oscillator

**RF output**

- Supply voltage amplifier
- Peak detector
- Limiter

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**EER**

- DC power consumption possible
- Compensation of AM/PM-distortion possible

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**UHF/AMTD example**

- ACPR = 60 dB
- ACPR = 40 dB
- ACPR = 30 dB
- ACPR = 20 dB
- ACPR = 10 dB
- ACPR = 0 dB
- ACPR = -10 dB
- ACPR = -20 dB
- ACPR = -30 dB
- ACPR = -40 dB

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**UMTS example**

- ACPR = 60 dB
- ACPR = 40 dB
- ACPR = 30 dB
- ACPR = 20 dB
- ACPR = 10 dB
- ACPR = 0 dB
- ACPR = -10 dB
- ACPR = -20 dB
- ACPR = -30 dB
- ACPR = -40 dB
Adaptive Bias

- Varying/Switching of Bias-Voltage depending on Input Power Level
- Selection of Operating Point with high PAE
- Applicably for nearly each type of Amplifier

![Bias Diagram](image)

Adaptive Bias

- Single tone PAE for switched $V_{DG}$ with $V_G$ kept constant
- Simply to implement Concept
- Stability guaranteed
- Possible problems:
  - DC-DC converter with high efficiency necessary
  - Possible Linearity Change (can increase and decrease) especially for HCAs
Summary

- Digital Realization required to achieve Accuracy
- Problem of Stability for high Bandwidth Application
- Higher Bandwidths (Oversampling) necessary, depending on Order of IMD cancellation
- Predistortion gives best Results while keeping Efficiency high (valid for high Output Levels > 40dBm)

Figure References

- Steve C. Cripps, “RF Power Amplifiers for Wireless Communications”, Artech House, 1999
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