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

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

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

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

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

\[ \eta_{PA} = \kappa \cdot 48\% \]
Class B
Class C
Class B and C – Circuit

Class B

\[ \eta_D = \kappa \cdot 78\% \]

\[ G = G_A - 6\text{dB} \quad (8\text{dB}) \]

\[ \eta_{PA} = \kappa \cdot 65\% \]

Class C

\[ \eta_D \to 100\% \]

\[ G \to 1 \]

\[ \eta_{PA} \to 0\% \]
Influence of Conduction Angle
Class F (HCA...harmonic controlled amplifier)
**hHCA** (half sinusoidally driven HCA)
Class F and hHCA – Circuit

\[ \eta_D = \kappa \cdot 100\% \]
\[ G = G_A - 5\text{dB} \quad (9\text{ dB}) \]
\[ \eta_{PA} = \kappa \cdot 87\% \]

Class F

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
Third Harmonic Peaking – Circuit

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

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

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

- Drain Current
- Ideal "strongly" non-linear
- 3rd order power series
- Gate voltage (normalized)

\[ I_{\text{max}} \]
\[ \frac{I_{\text{max}}}{2} \]
Linearity Aspects

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

- Ideal strongly nonlinear model
- Strong-weak nonlinear model
Amplifier Design – An Example

- Balanced Amplifier Configuration

Port 1
Z=50 Ohm

Port 2
Z=50 Ohm
Amplifier Design – Simulation

- Gate & Drain Waveforms

![Gate waveforms](image1)

![Drain waveforms](image2)
Amplifier Design – Simulation

- Dynamic Load Line & Power Sweep

**Dynamic Load Line**
- Voltage (V)
- IV_Curve (mA)
- Dynamic Load Line (mA)

**Power Sweep 1 Tone**
- Output Power (L, dBm)
- PAE (R)

Graphs showing the dynamic load line and power sweep results.
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
Spectral Regrowth

- 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
    \[ f(r) = \frac{\alpha_d r}{1 + \beta_d r^2} \quad g(r) = \frac{\alpha_\theta r^2}{1 + \beta_\theta r^2} \]
  - Taylor Series
  - Blum and Jeruchim Model
  - AM/AM- and AM/PM-conversion
AM/AM- and AM/PM-Conversion

- GaAs-PA
AM/AM- and AM/PM-Conversion

- LDMOS-PA

![Graph showing AM/AM- and AM/PM-Conversion](image)
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 → 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 $\rightarrow$ -31dB Cancellation
  - 2.5° Phase Error $\rightarrow$ -27dB Cancellation
- Well suited for narrowband application
**Cartesian Feedback**

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

**UMTS example:**

- Original signal
- Predistorted signal

**Graph:**
- Relative power vs. relative frequency
- RF-output
- Baseband input
- Modulator
- Main amp.
- Demodulator
- Local oscillator
- OPAs
- Main amp.
- Local oscillator
- I, Q
- OPAs
- I, Q
- Demodulator
- Modulator
- Main amp.
Digital Predistortion

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

- Predistorter has inverse function of amplifier
- Leads to infinite bandwidth (!)
- Hard to realize (accuracy)
Analog Predistortion

Possible Realizations:
LINC (Linear Amplification by Nonlinear Components)

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

**UMTS example:**

![Graph showing AC PR1 > 60dB, ACPR > 60dB, ACPR = 16dB, ACPR = 29dB]
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:

- **Magnitude**
- **Phase**

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UMTS example:

- ACPR₁ > 60dB
- ACPR₂ > 60dB
- ACPR₁ = 33dB
- ACPR₂ = 40dB
- ACPR₁ = 51dB
- ACPR₂ = 36dB
- ACPR₁ = 53dB
- ACPR₂ = 49dB
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
Adaptive Bias

- Single tone PAE for switched $V_{DD}$ 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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