RF Power Amplifier Design

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June 11, 2001

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Contents

- Basic Amplifier Concepts
  - Class A, B, C, F, hHCA
  - Linearity Aspects
  - Amplifier Example
- Enhanced Amplifier Concepts
  - Feedback, Feedforward, ...
  - Predistortion
  - LINC, Doherty, EER, ...

Efficiency Definitions

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

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

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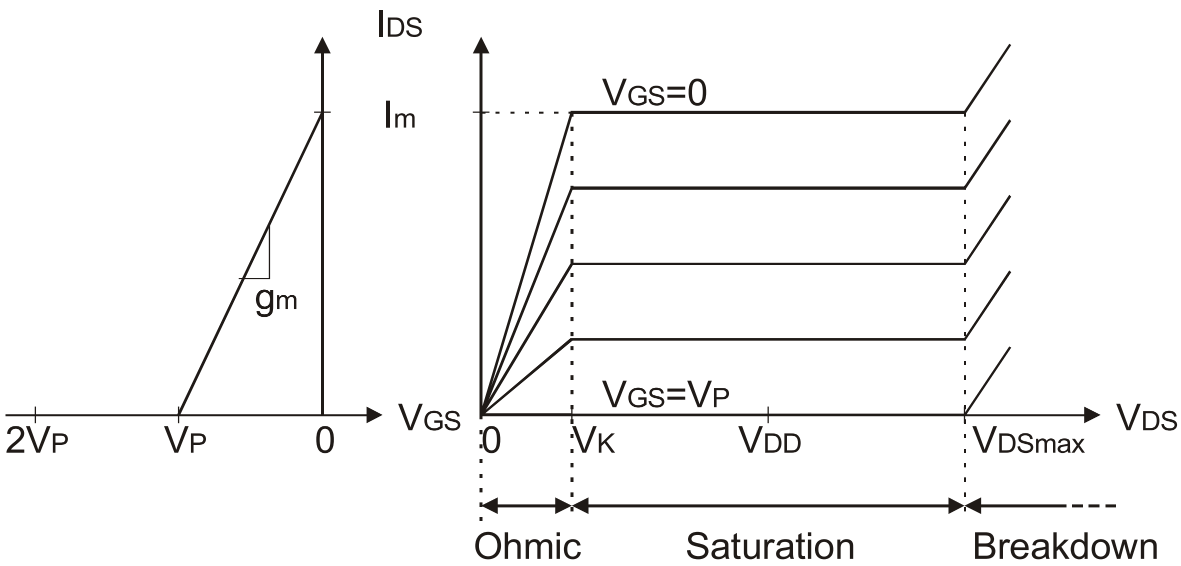
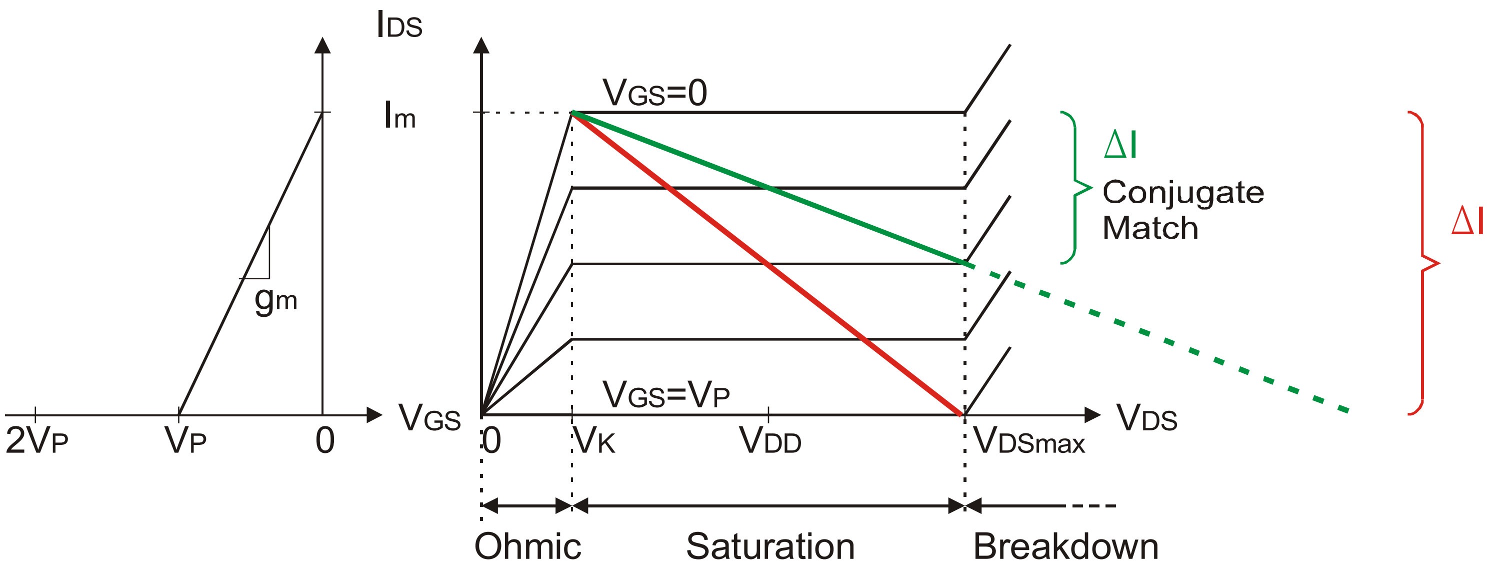
Ideal FET Input and Output Characteristics



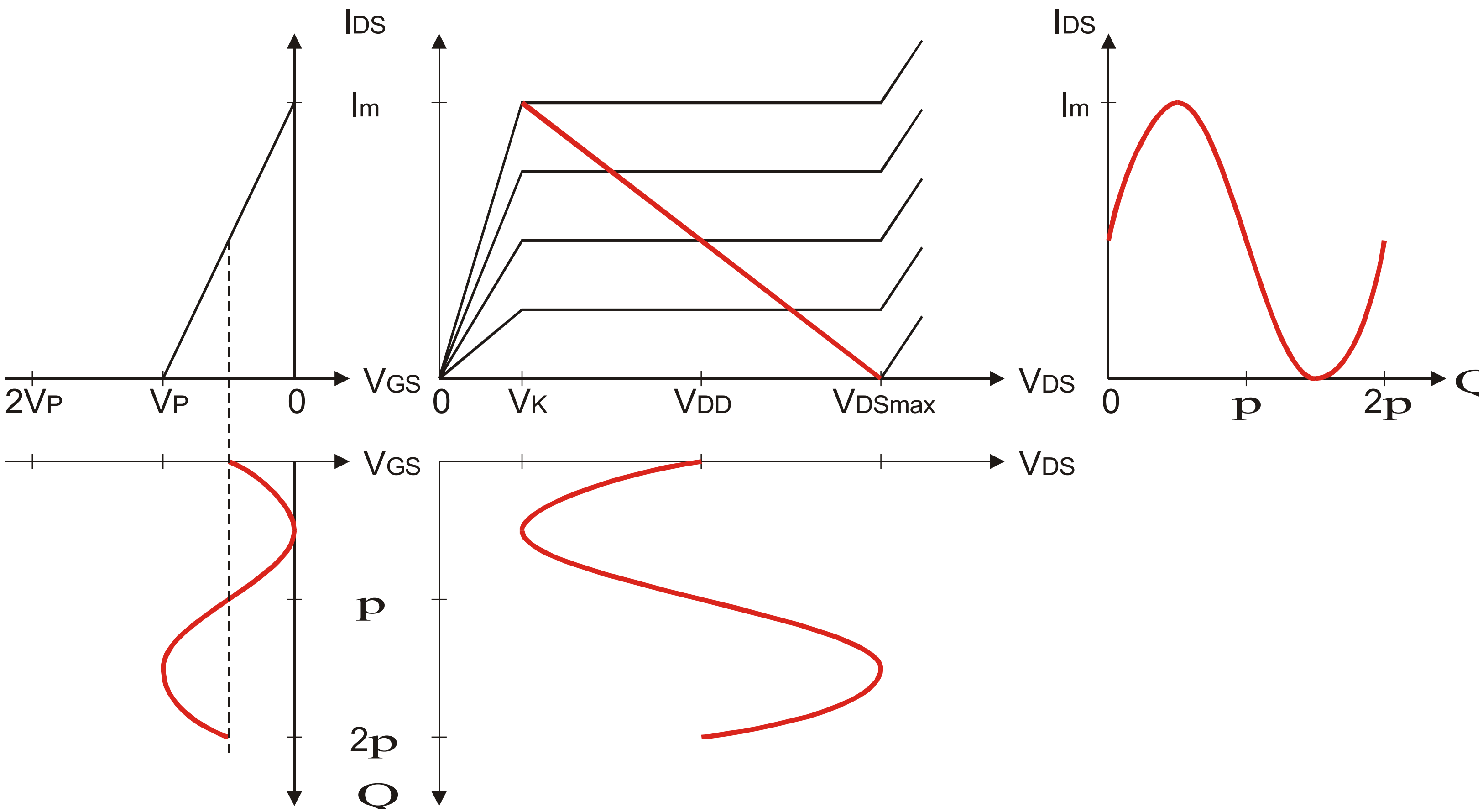
$$\kappa = \frac{V_{DD} - V_K}{V_{DD}}$$

Maximum Output Power Match



$$R_{OPT} = \frac{V_{DS\max} - V_K}{I_m}$$

Class A



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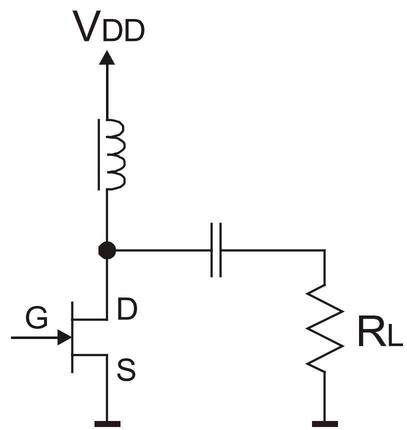
Class A – Circuit

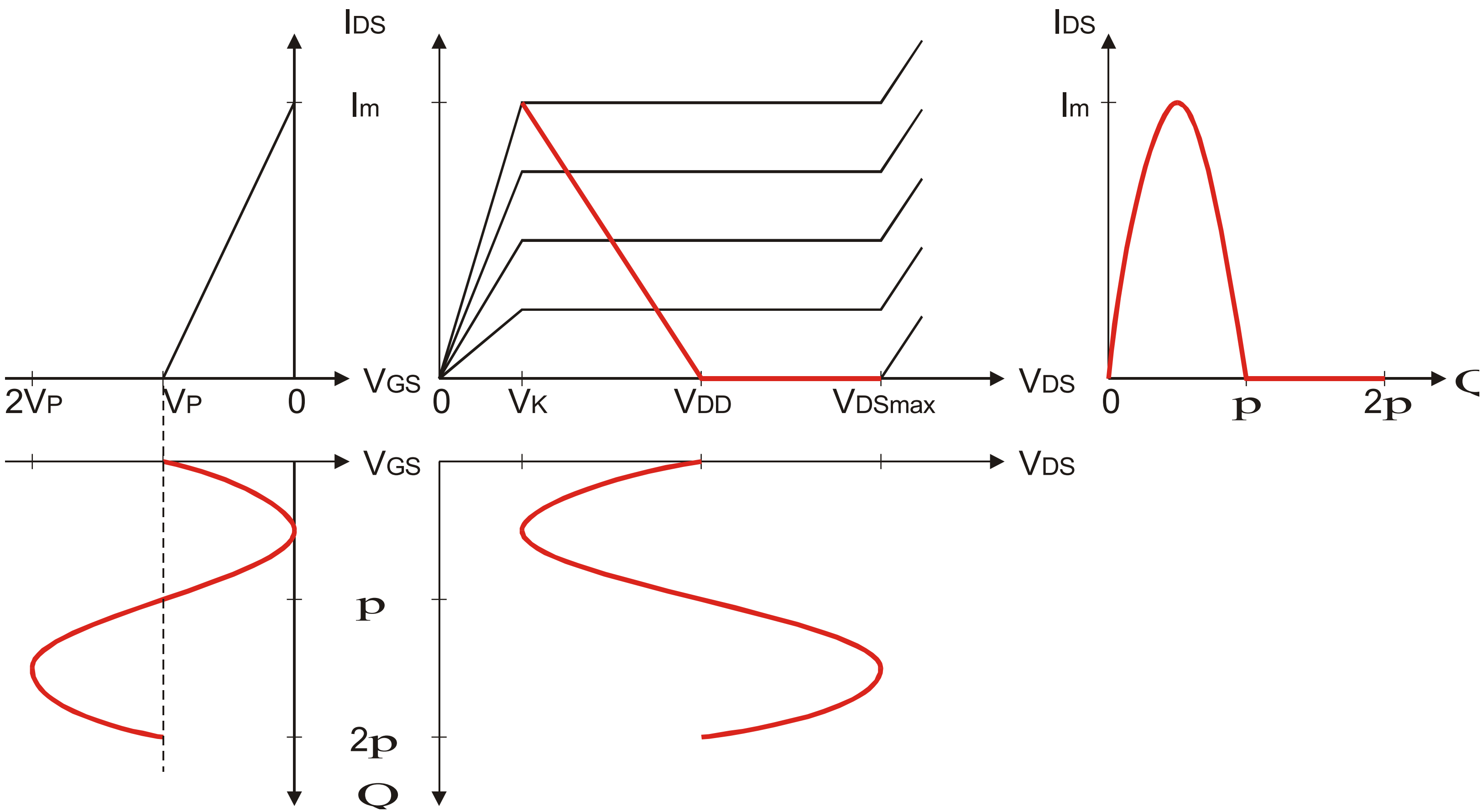


$$\eta_D = \kappa \cdot 50\%$$

$$G = G_A \quad (\text{e.g.}\, 14\,\text{dB})$$

$$\eta_{\text{PA}} = \kappa \cdot 48\%$$

Class B



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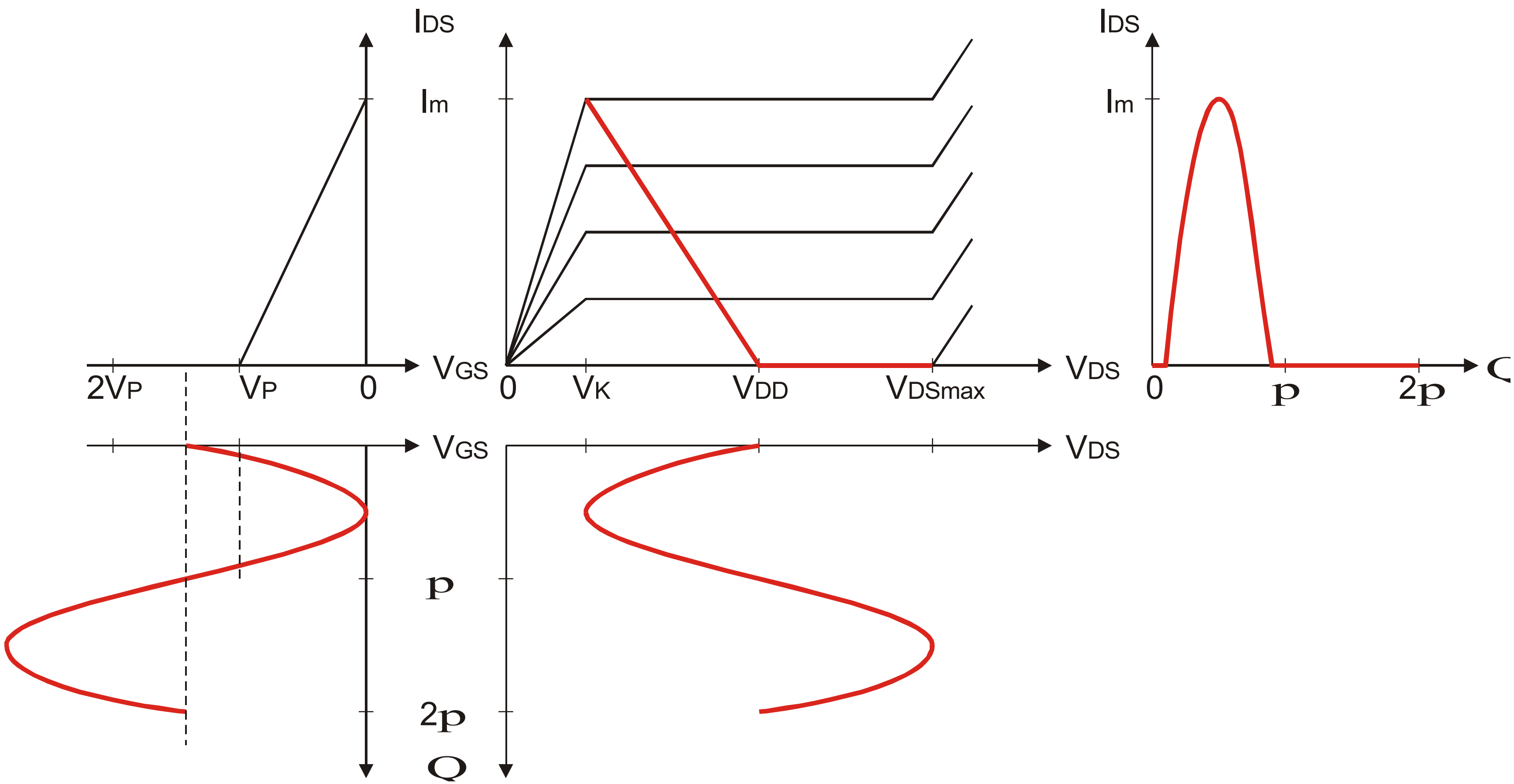
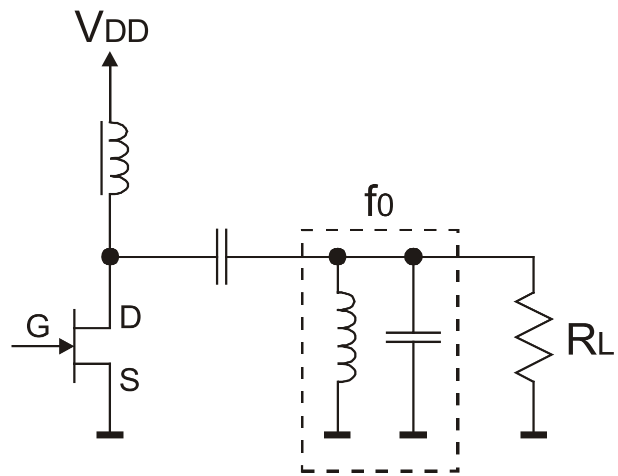
Class C

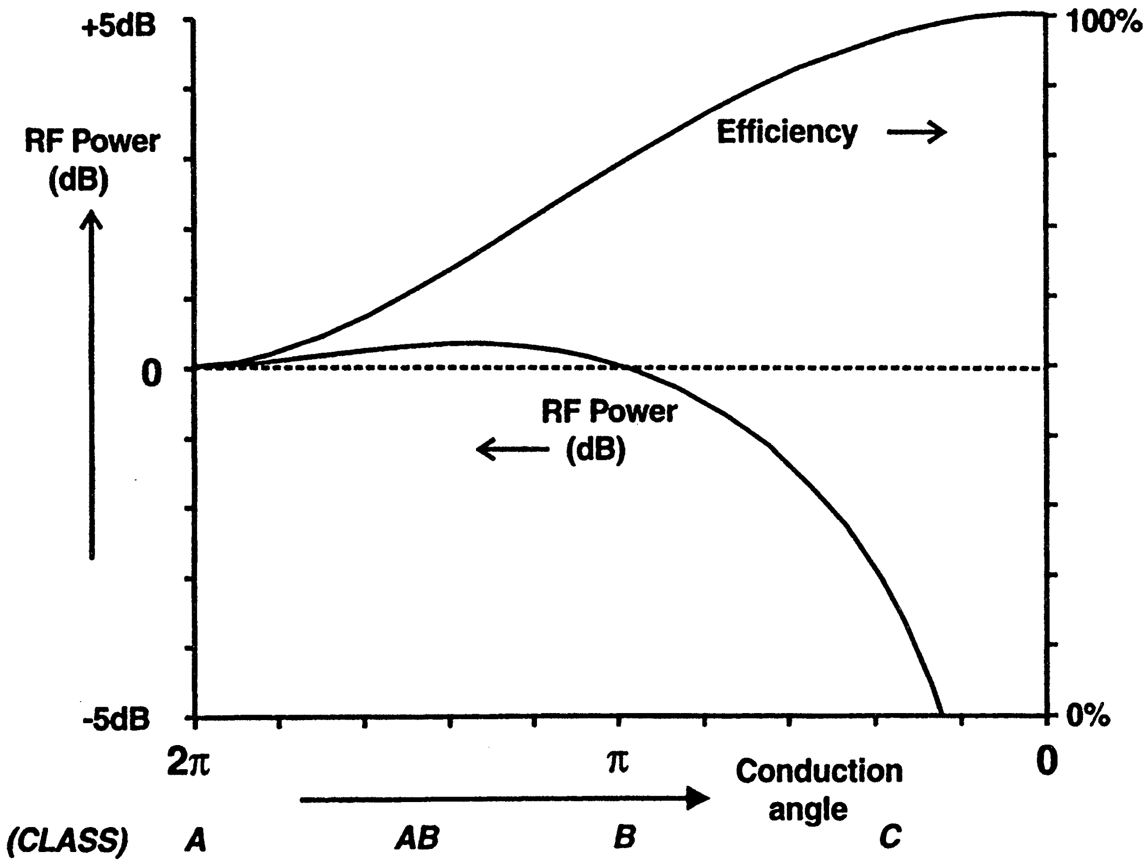


Class B and C – Circuit



Class B	Class C
$\eta_D = \kappa \cdot 78\%$	$\eta_D \to 100\%$
$G = G_A - 6\text{dB} \quad (8\,\text{dB})$	$G \to 1$
$\eta_{\text{PA}} = \kappa \cdot 65\%$	$\eta_{\text{PA}} \to 0\%$

Influence of Conduction Angle



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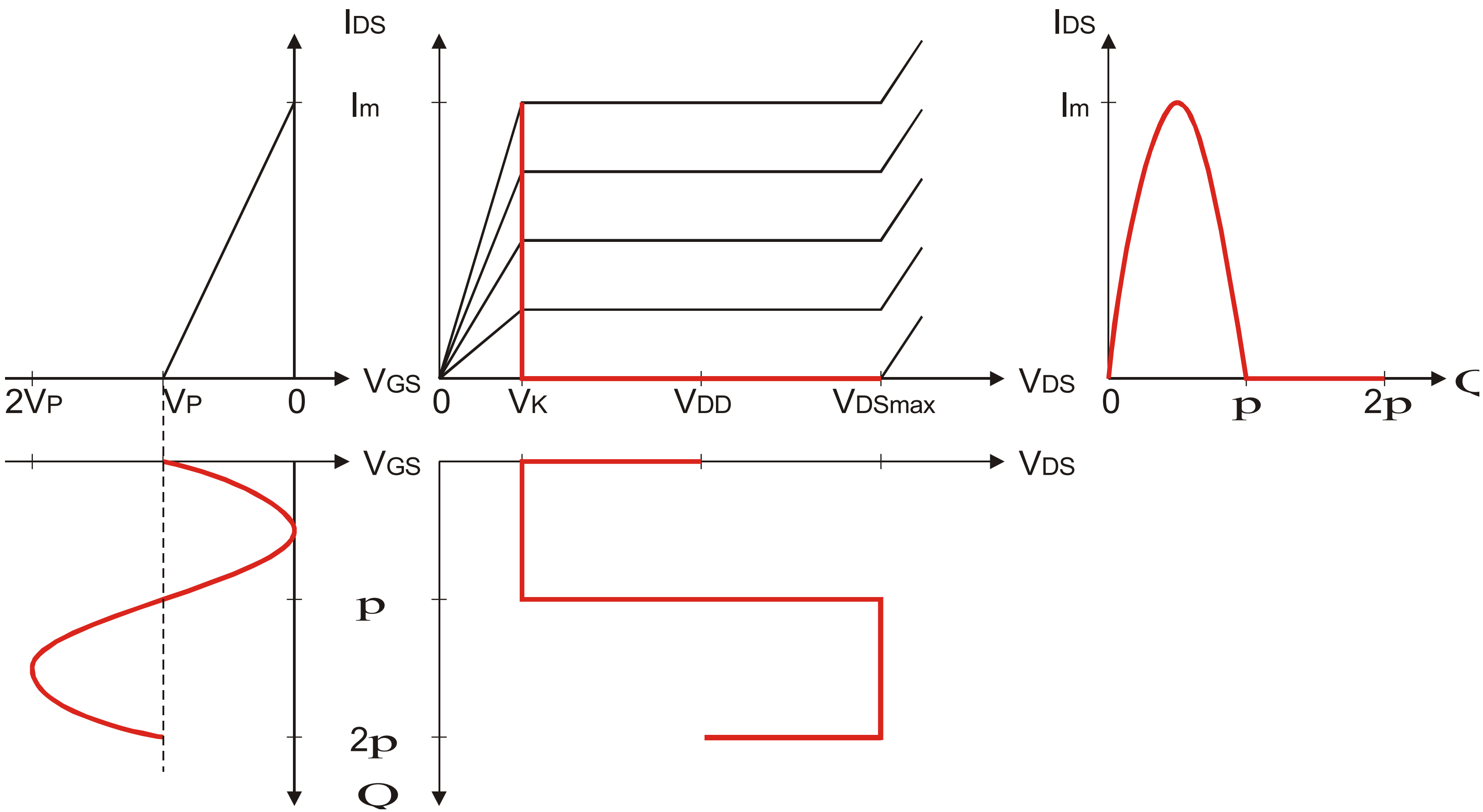
Class F (HCA ... harmonic controlled amplifier)



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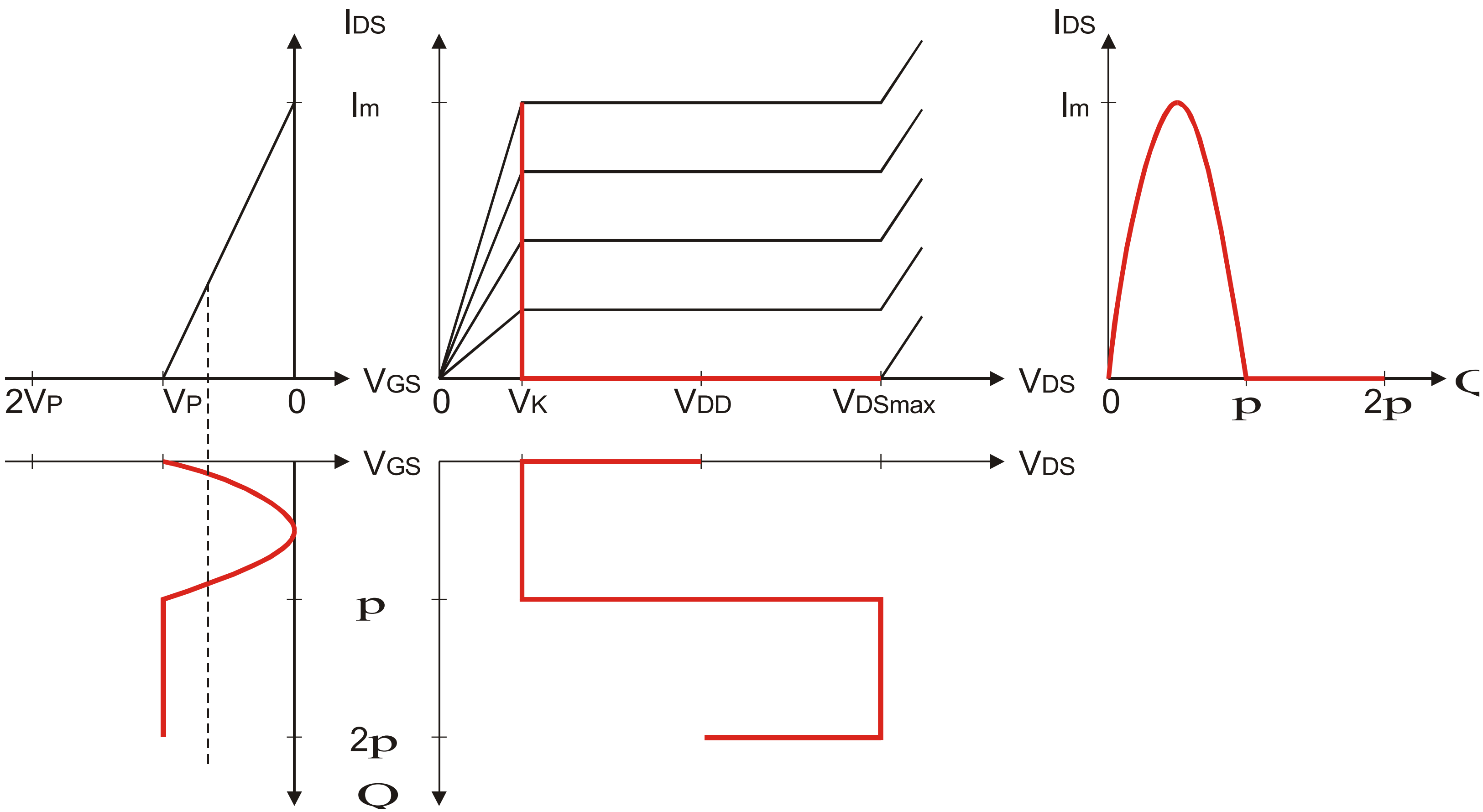
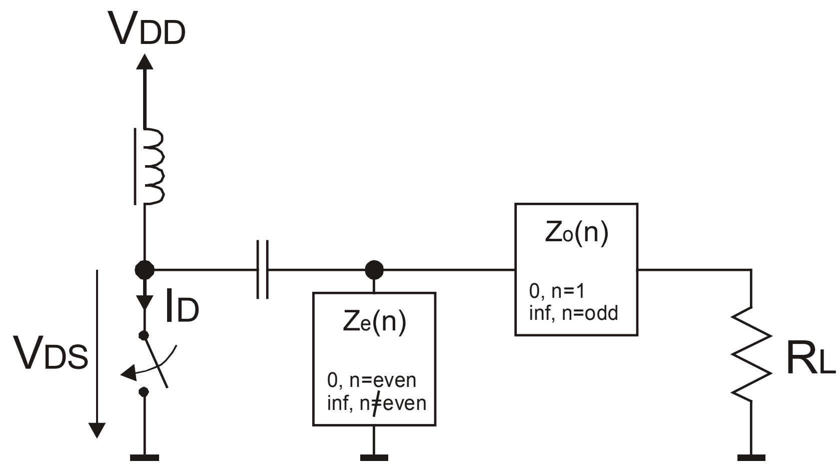
hHCA (half sinusoidally driven HCA)

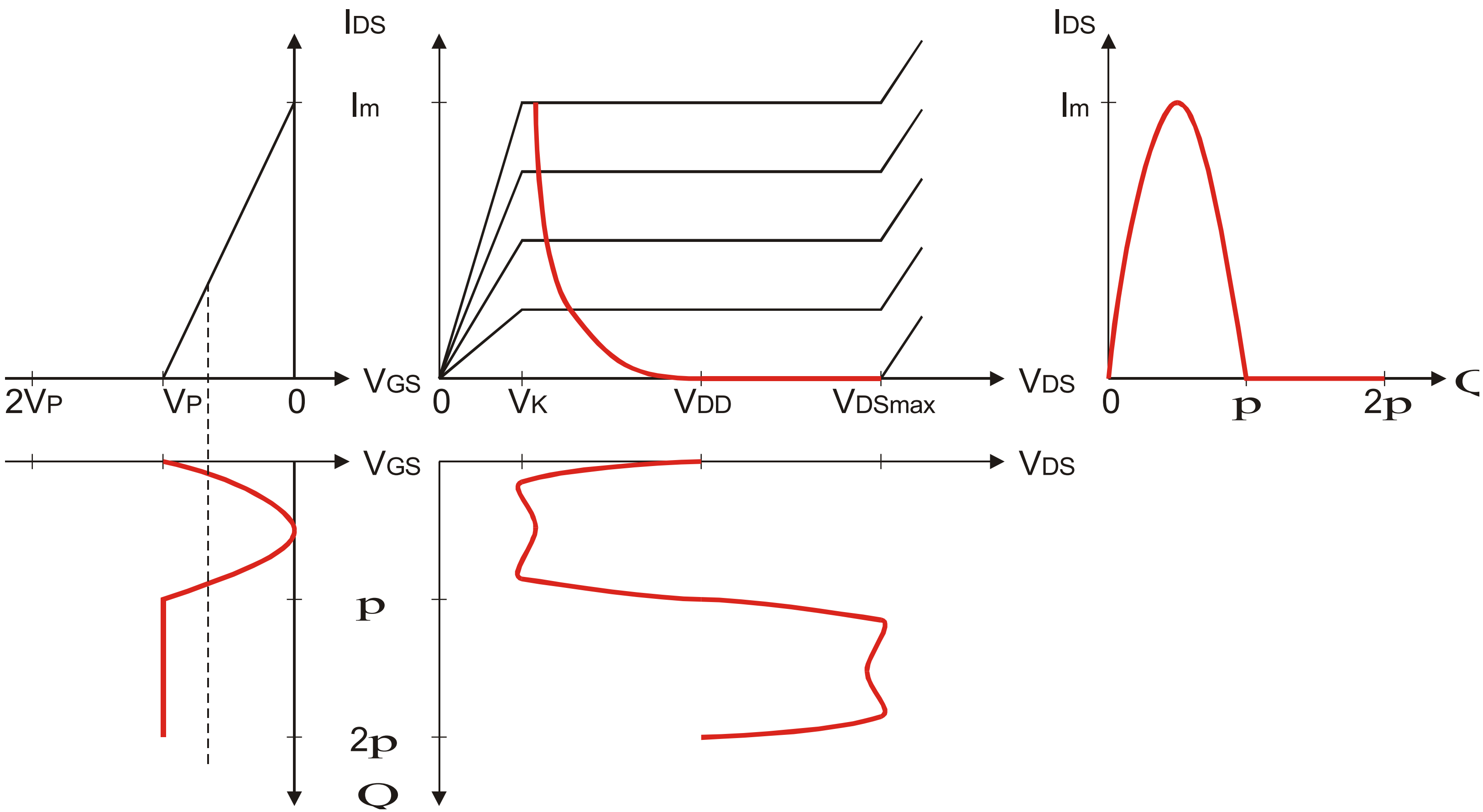


Class F and hHCA – Circuit



<u>Class F</u>	<u>hHCA</u>
$\eta_D = \kappa \cdot 100\%$	$\eta_D = \kappa \cdot 100\%$
$G = G_A - 5\text{dB} \quad (9\text{ dB})$	$G = G_A + 1\text{dB} \quad (15\text{ dB})$
$\eta_{\text{PA}} = \kappa \cdot 87\%$	$\eta_{\text{PA}} = \kappa \cdot 96\%$

hHCA – Third Harmonic Peaking



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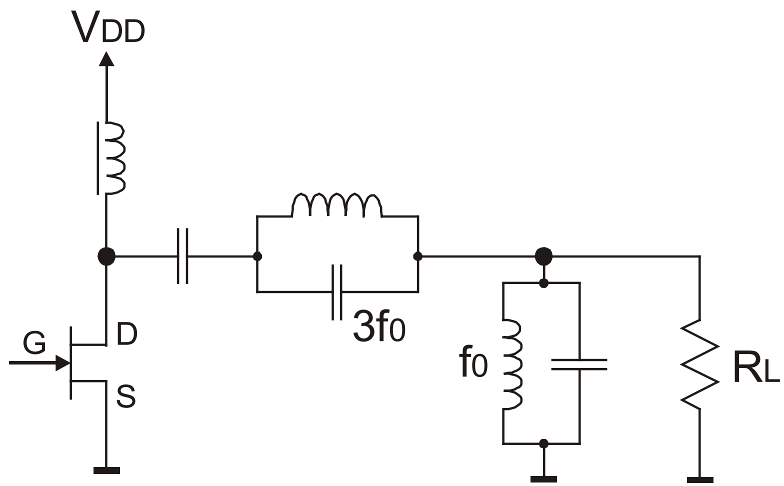
Third Harmonic Peaking – Circuit

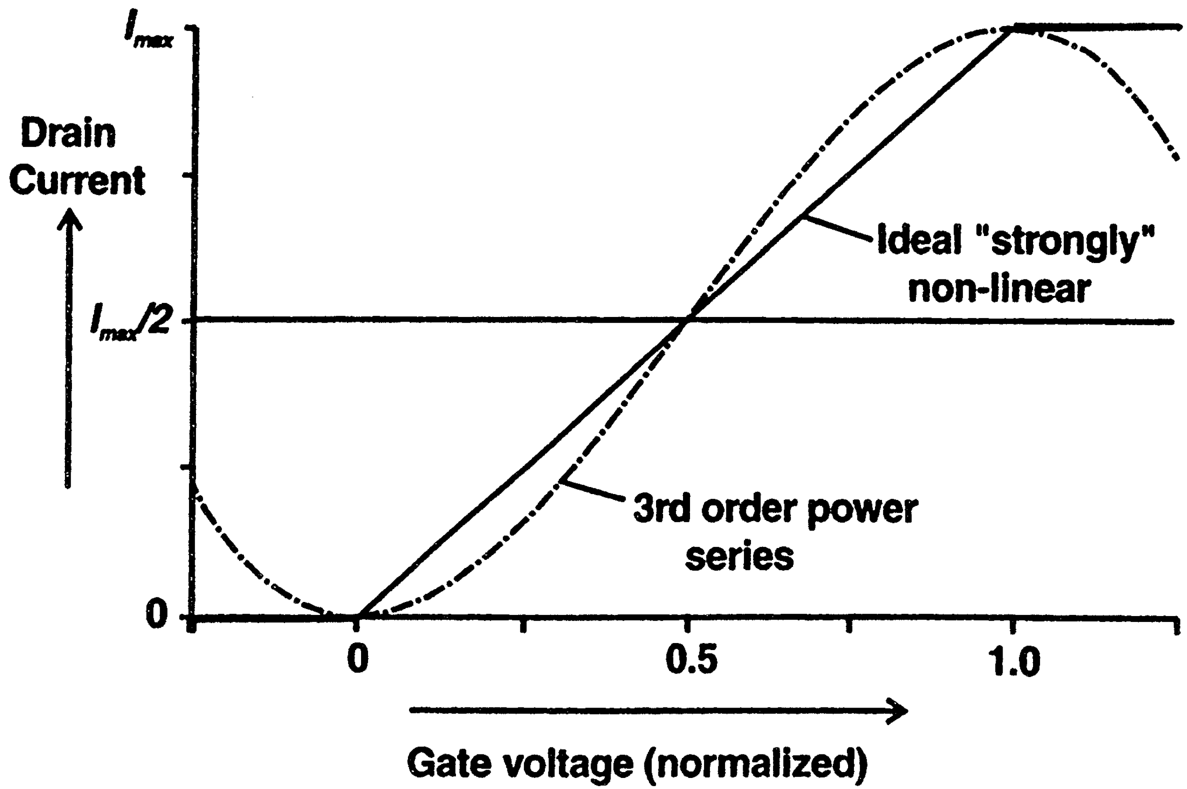


$$\eta_D = \kappa \cdot 91\%$$

$$G = G_A + 0.6\text{dB} \quad (14.6\,\text{dB})$$

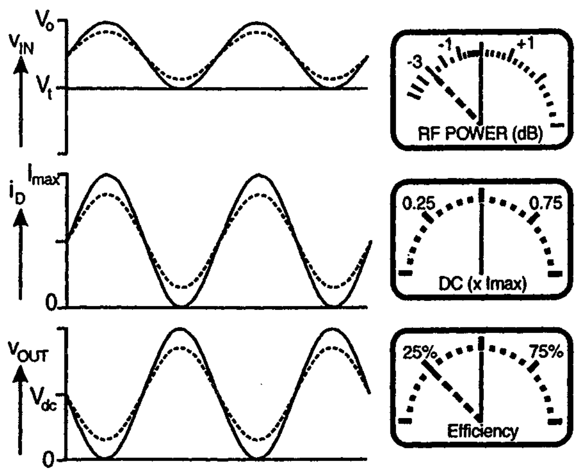
$$\eta_{\text{PA}} = \kappa \cdot 87\%$$

Linearity Aspects

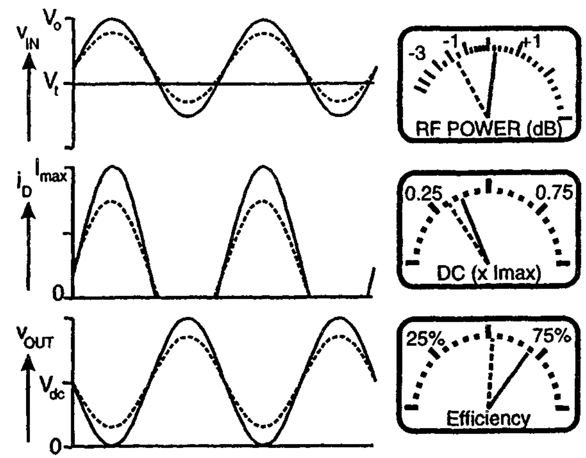


Linearity Aspects

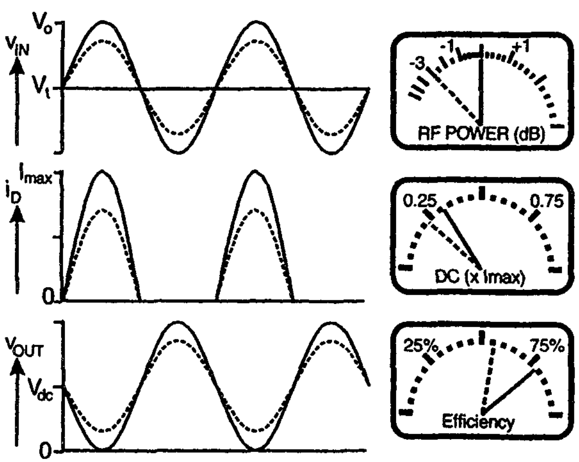
- Class A



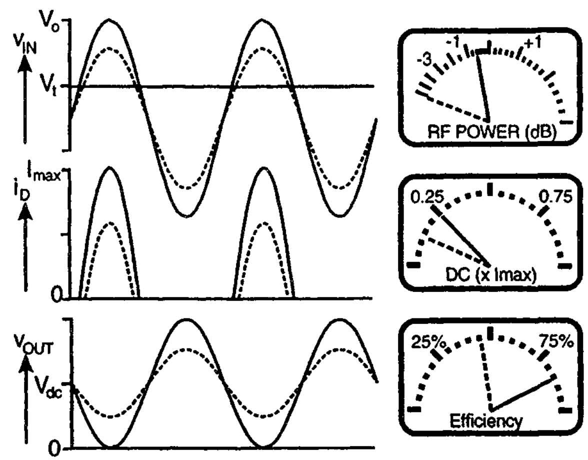
- Class AB



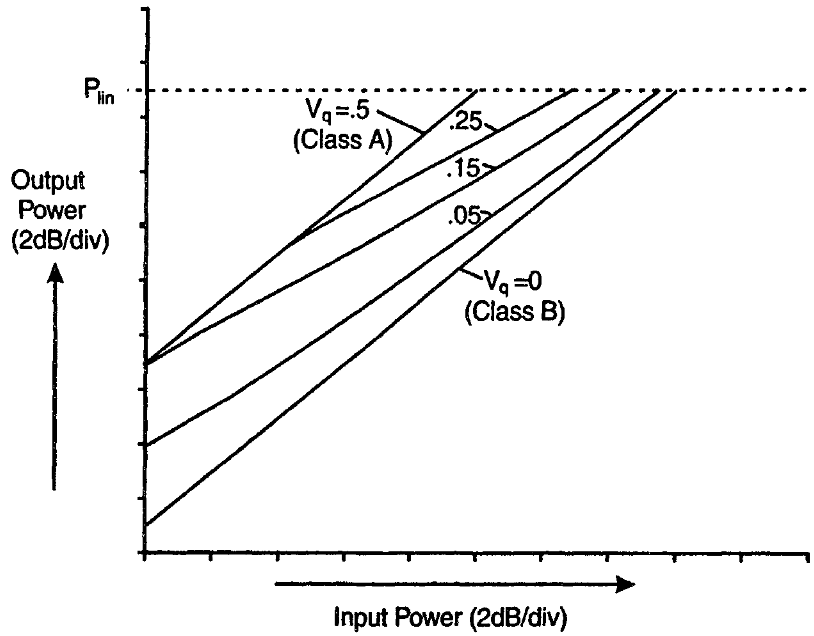
- Class B

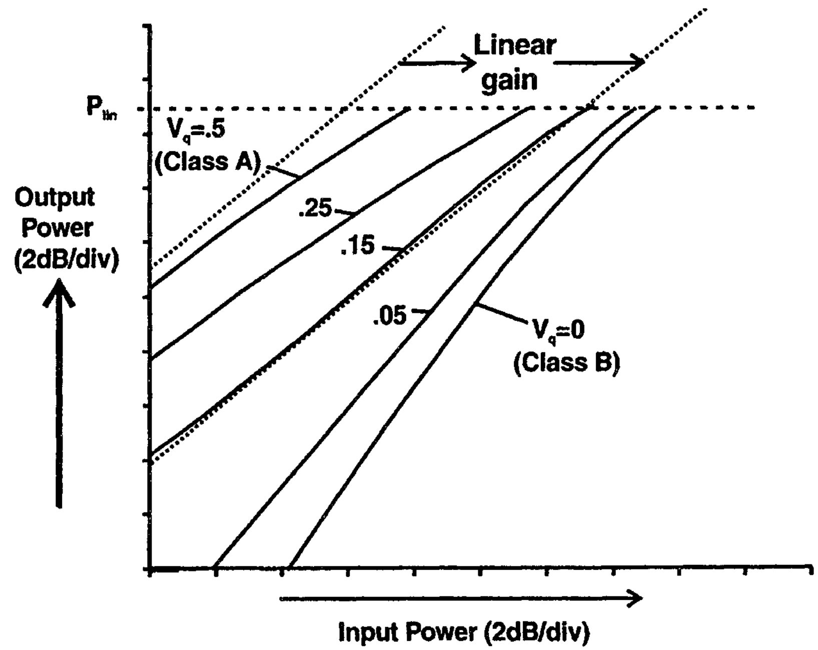


- Class C



Linearity Aspects





- Ideal strongly nonlinear model
- Strong-weak nonlinear model

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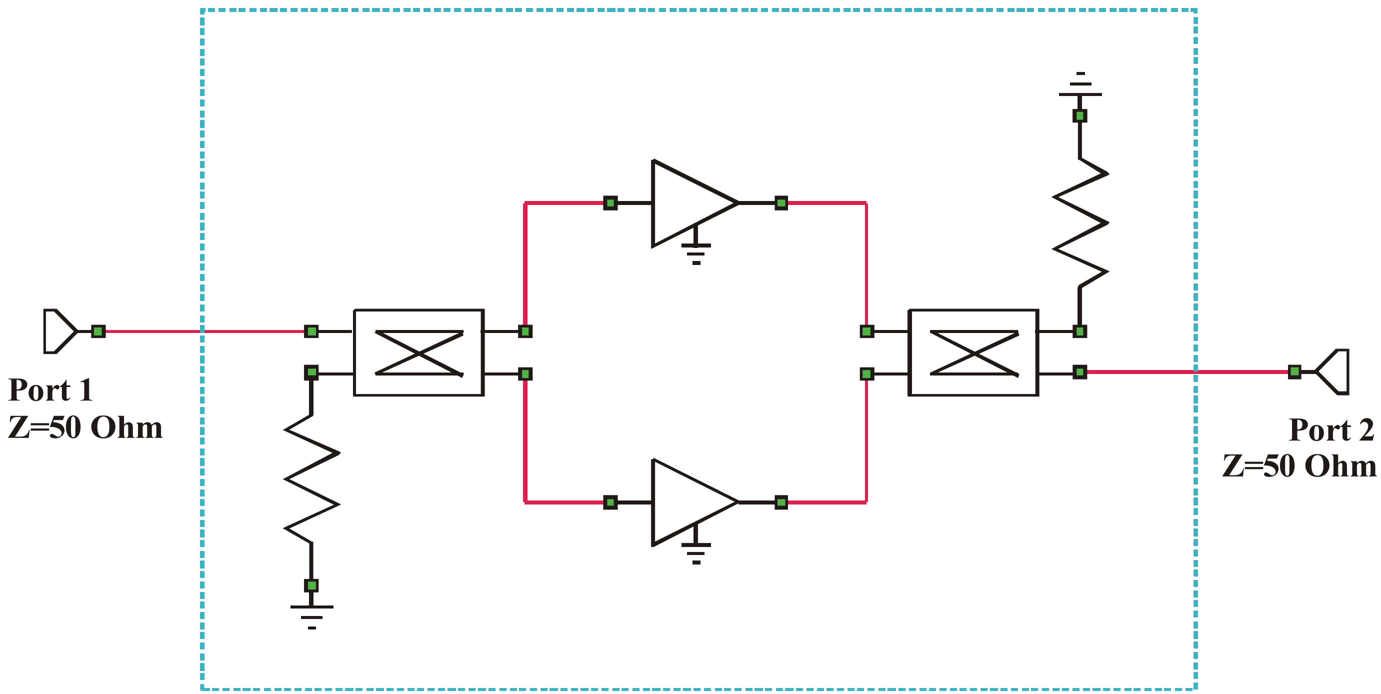
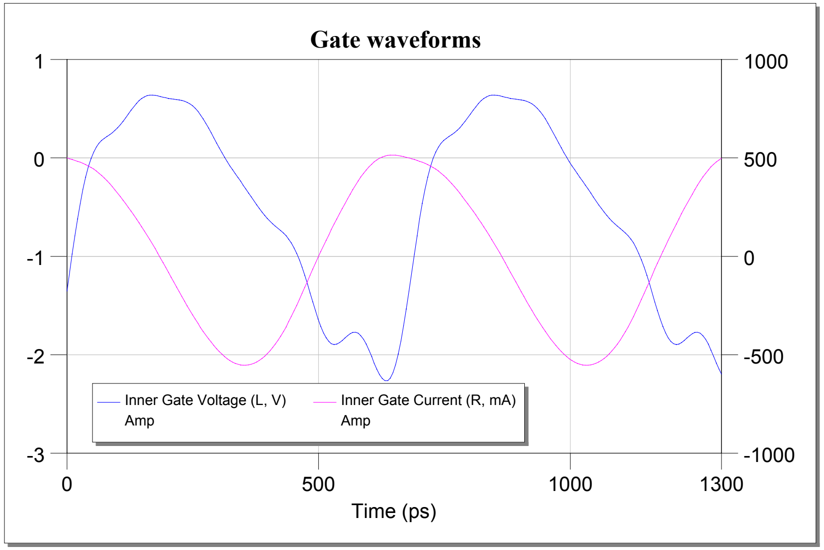
Amplifier Design – An Example

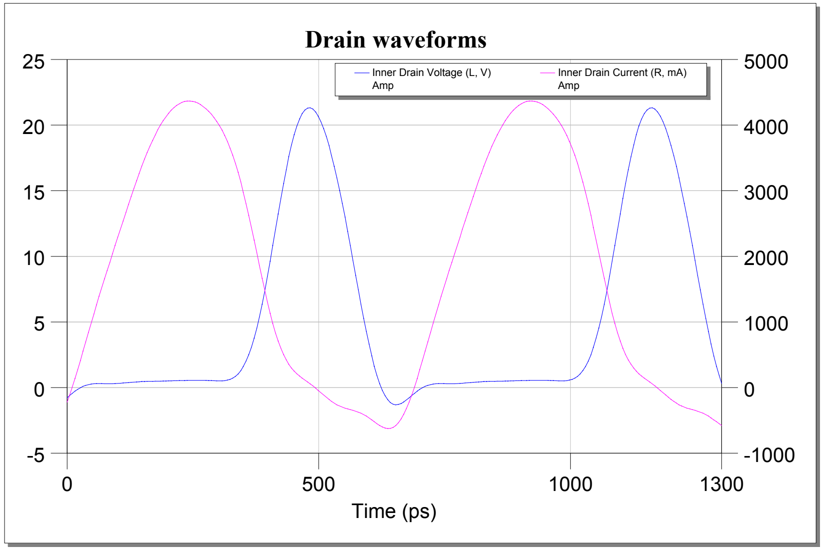
- Balanced Amplifier Configuration



Amplifier Design – Simulation

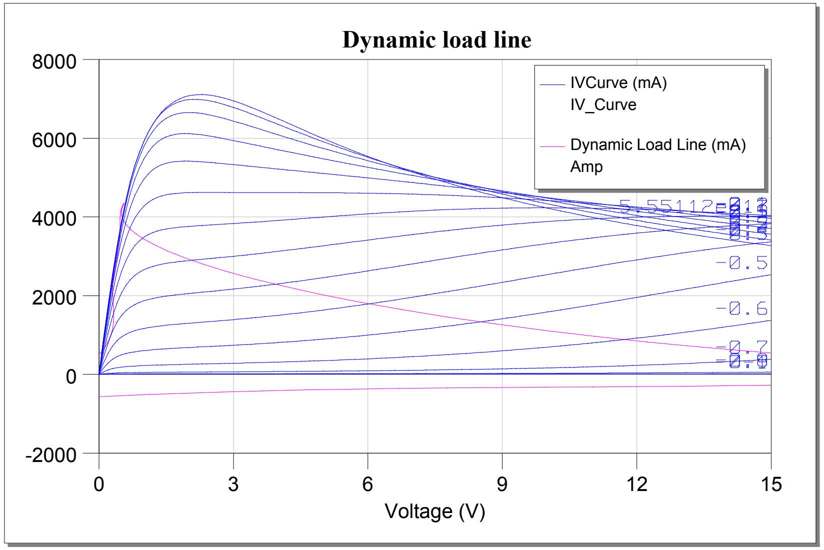
- Gate & Drain Waveforms

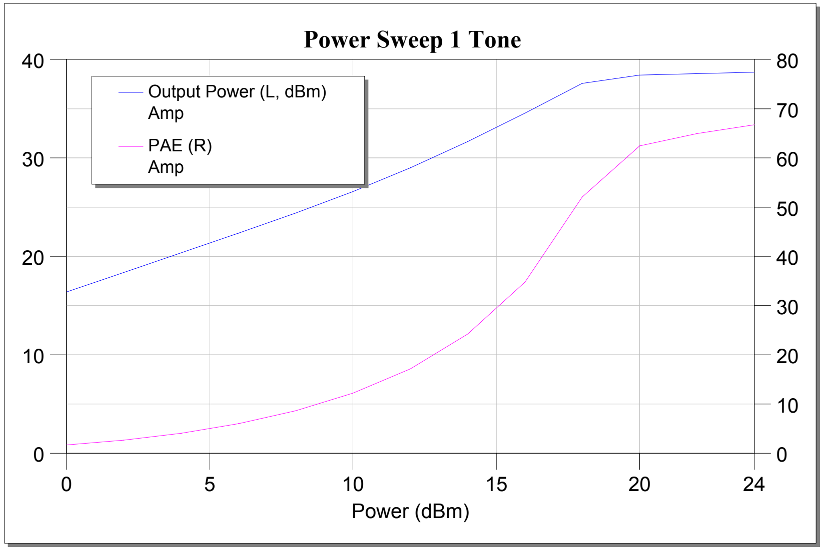




Amplifier Design – Simulation

- Dynamic Load Line & Power Sweep





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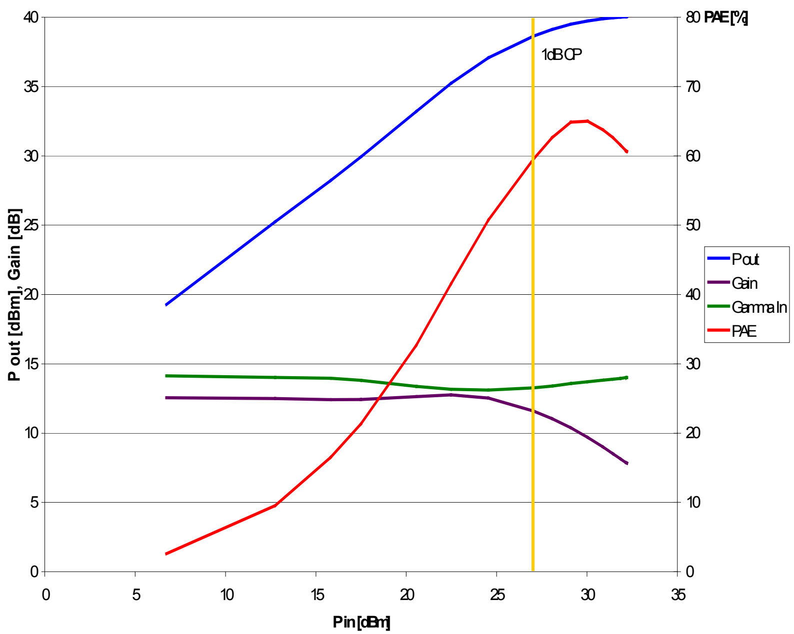
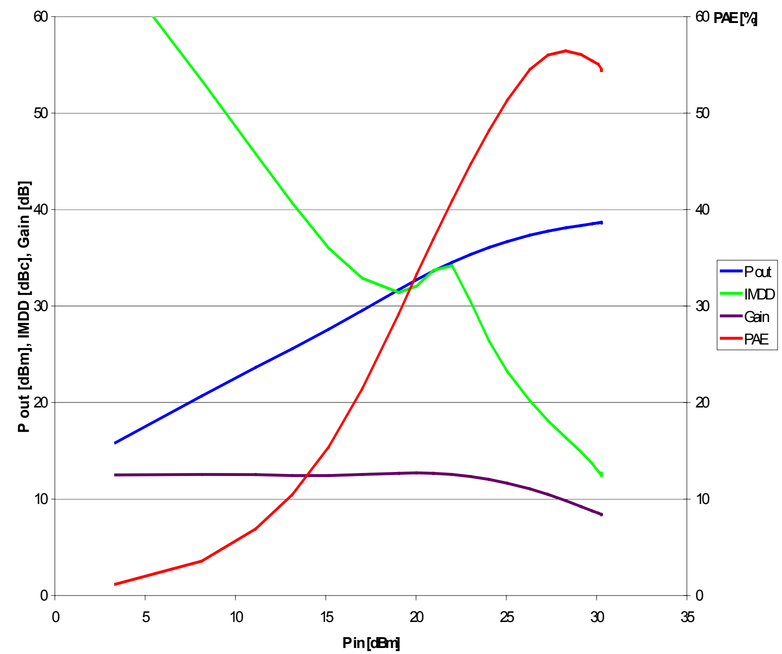
Amplifier Design – Measurements

- Single Tone & Two Tone





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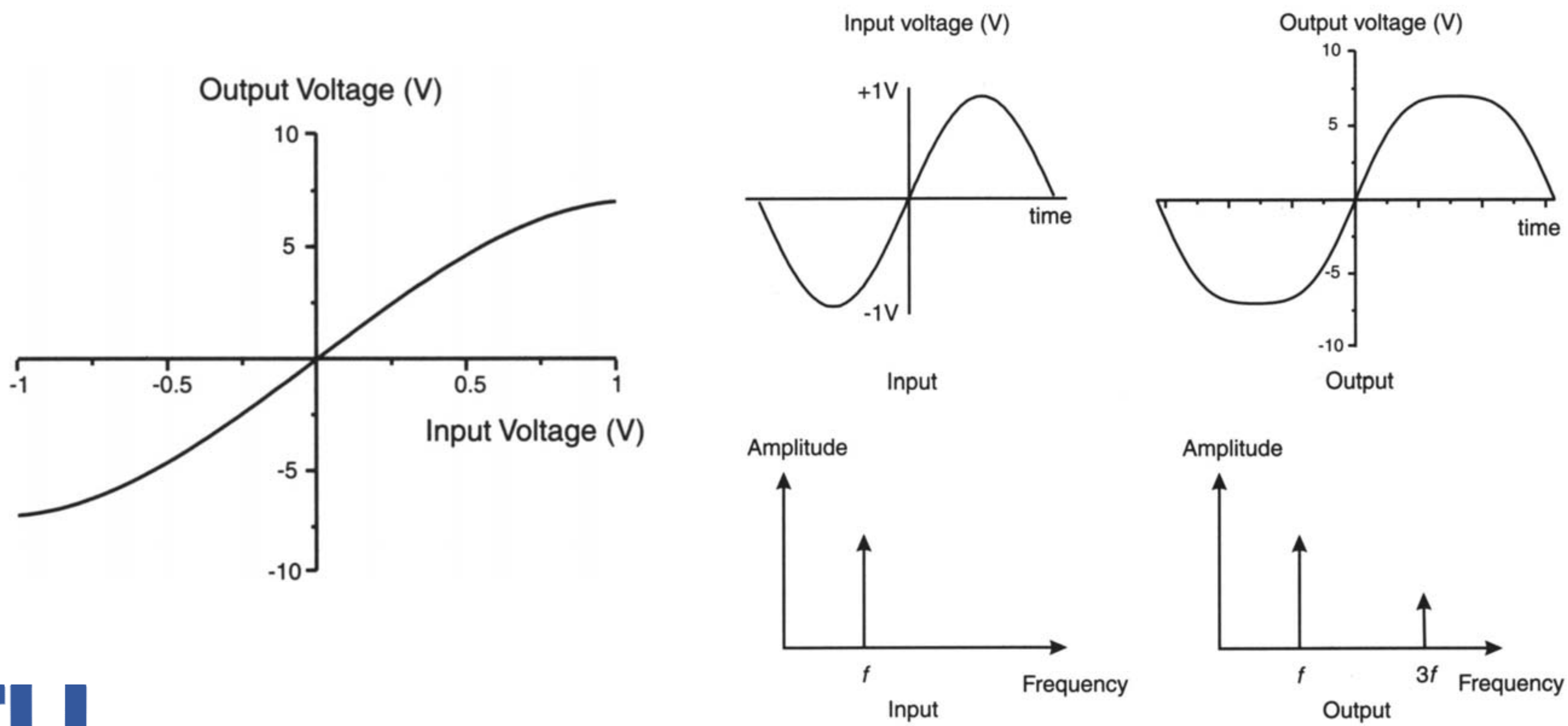
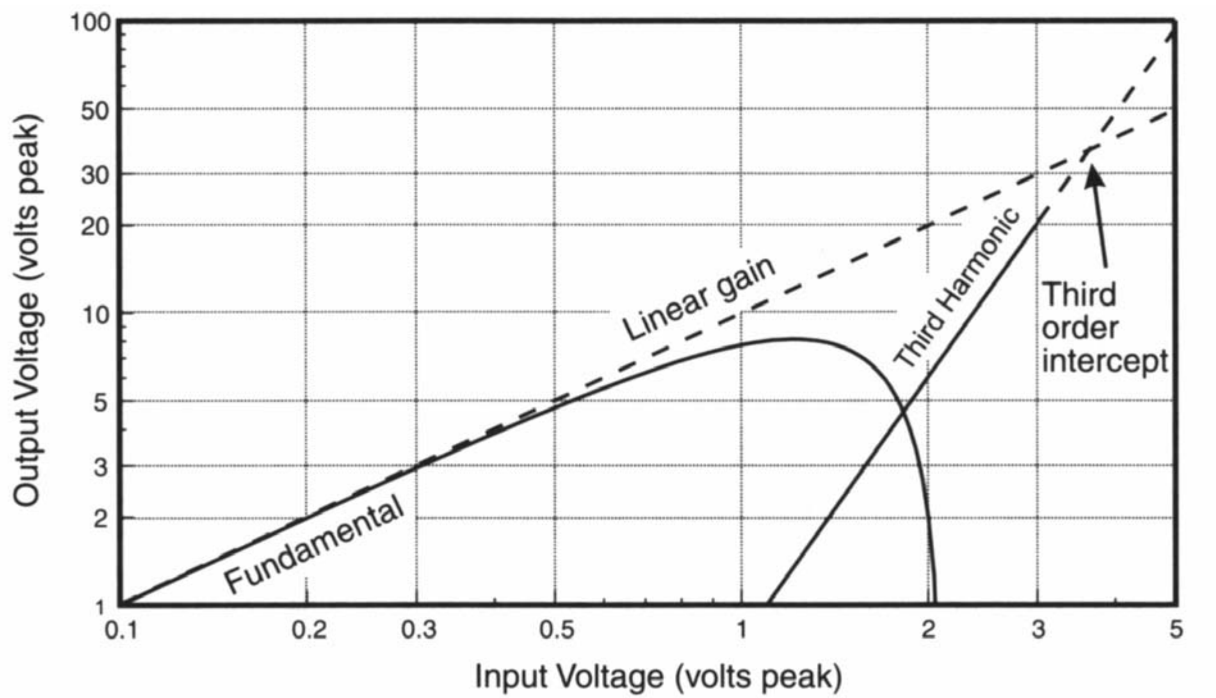
Amplifier Nonlinearity

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



Amplifier Nonlinearity

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



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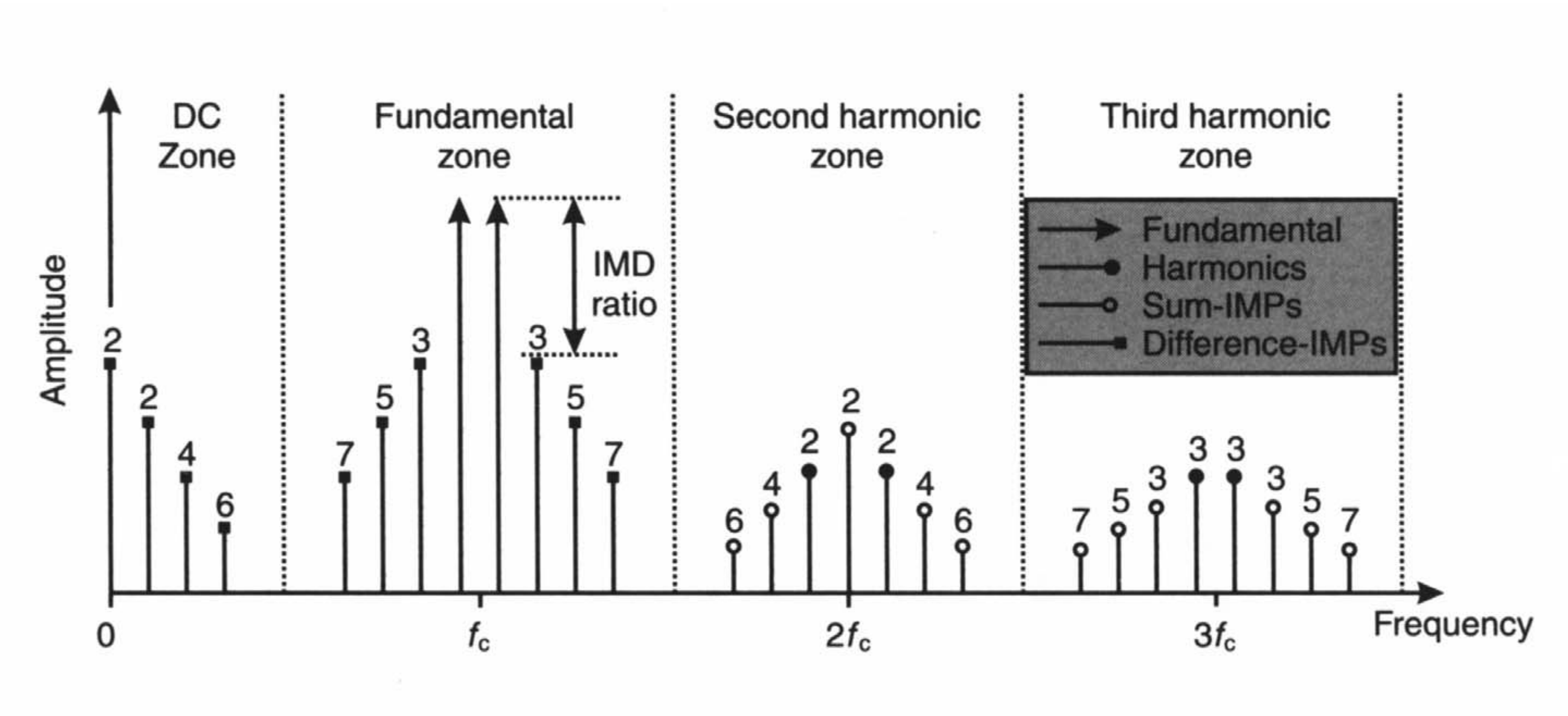
Nonlinearity leads to?

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

Intermodulation and Harmonics



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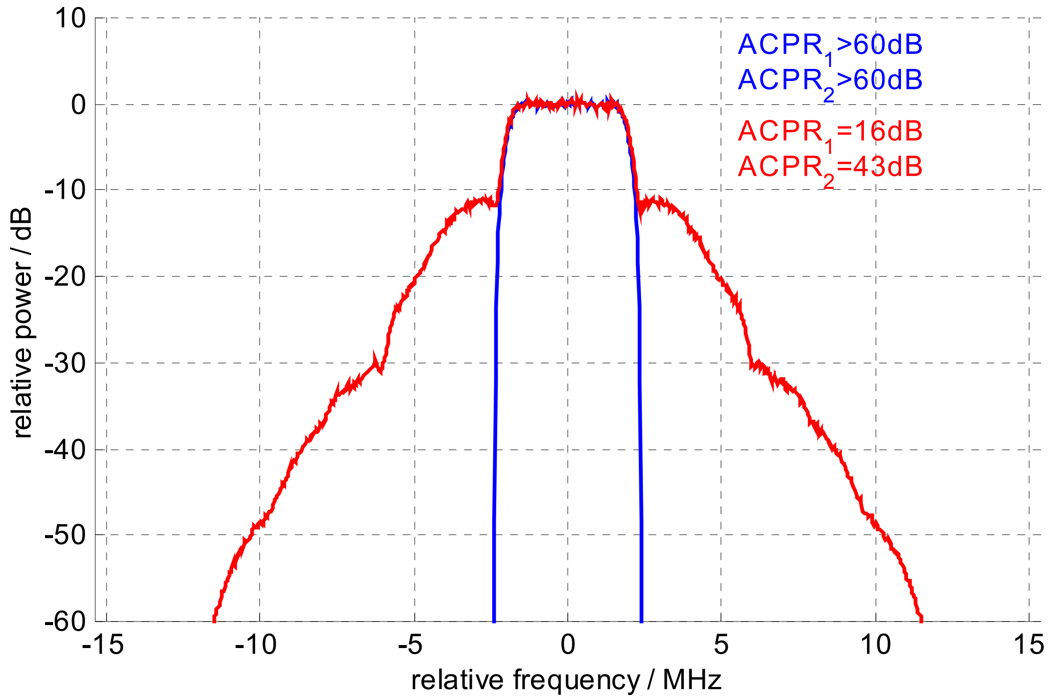
Spectral Regrowth



- Energy in adjacent Channels
- ACPR (Adjacent Channel Leakage Power Ratio) increases

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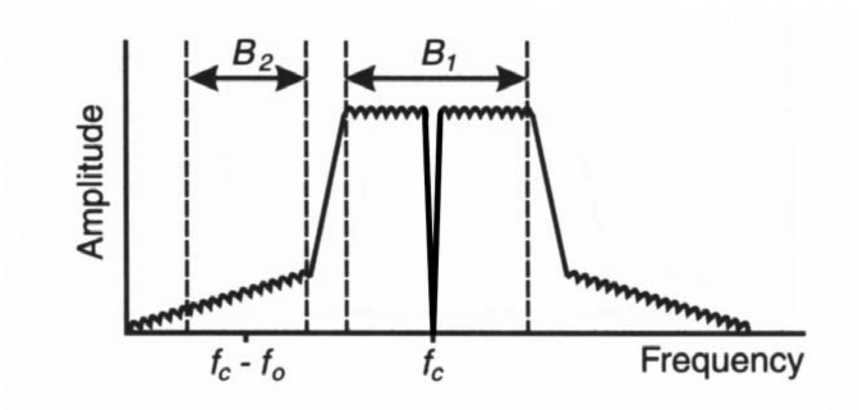
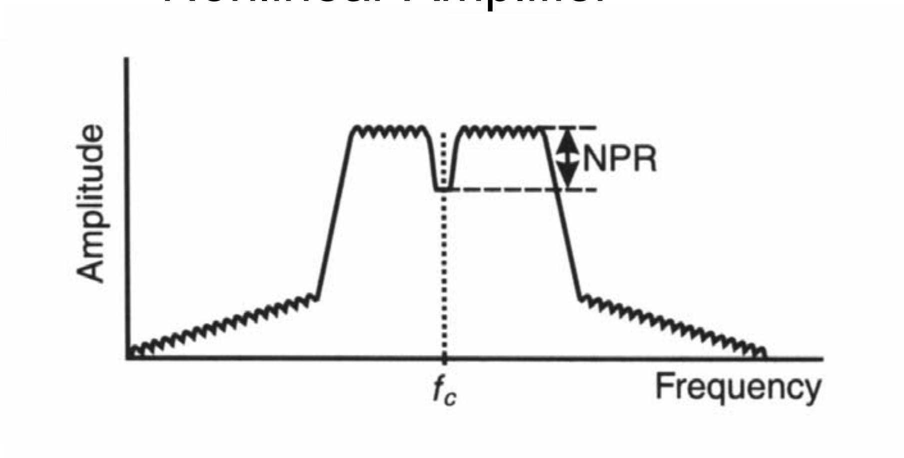
Reduced NPR (Noise Power Ratio)

- Input Signal



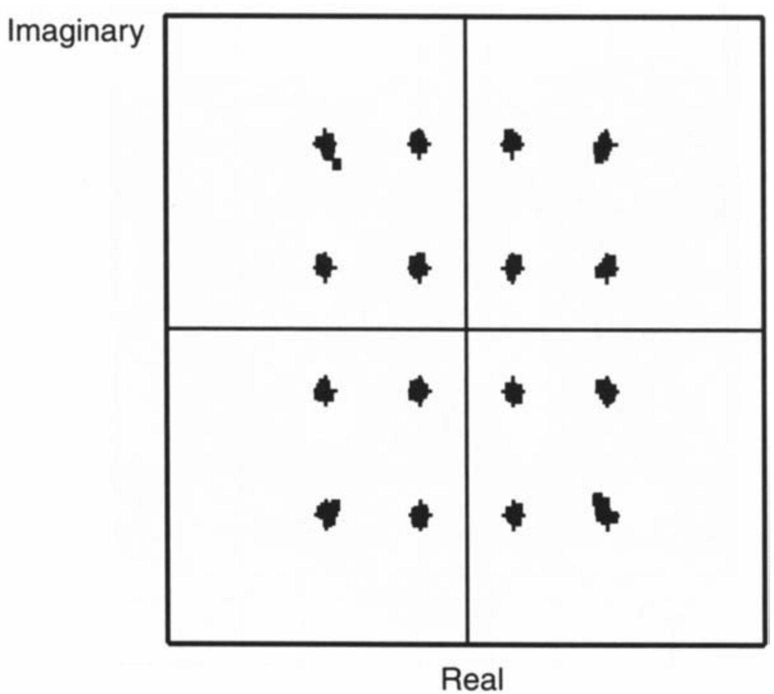
- Output Signal of Nonlinear Amplifier



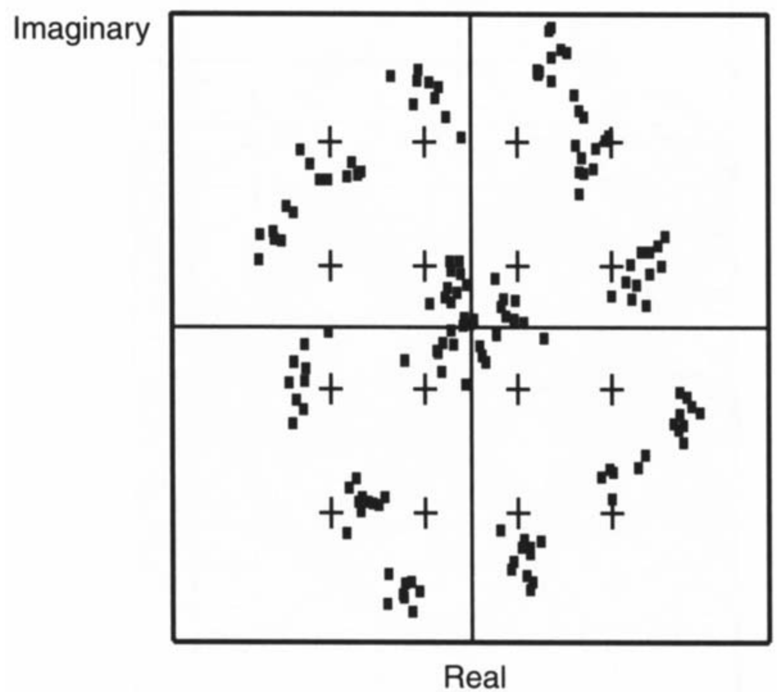
- Degradation of Inband SNR
- „Noisy“ Constellation

Constellation Deformation

- Input Signal



- Output Signal of Nonlinear Amplifier (with Gain- and Phase-Distortion)



Modeling of Nonlinearities

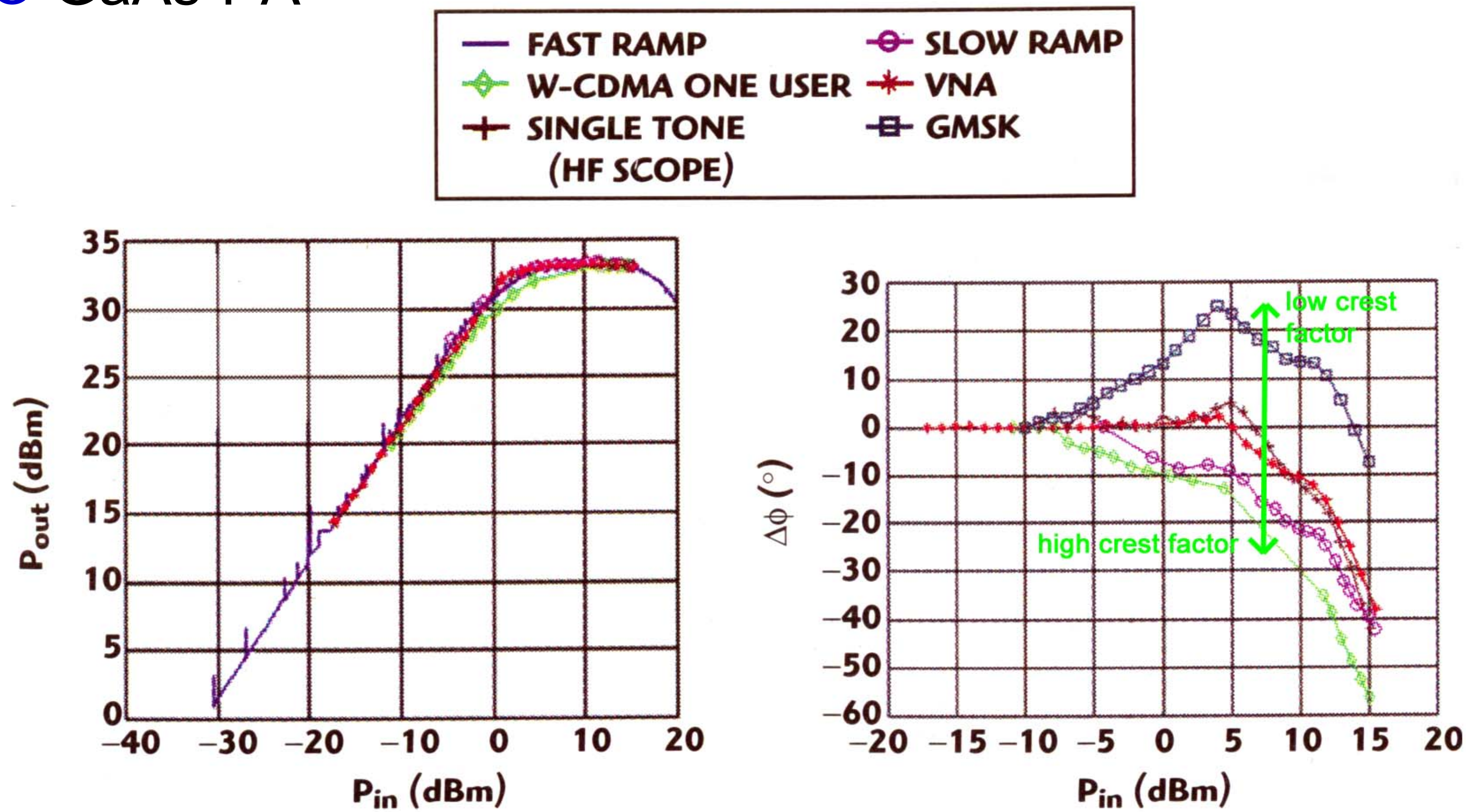
- with Memory-Effects
  - Volterra Series (=„Taylor Series with Memory“)

- without Memory-Effects
  - Saleh Model $f(r) = \dfrac{\alpha_a r}{1+\beta_a r^2}$ $\quad g(r) = \dfrac{\alpha_\Theta r^2}{1+\beta_\Theta r^2}$
  - Taylor Series
  - Blum and Jeruchim Model
  - AM/AM- and AM/PM-conversion

better performance

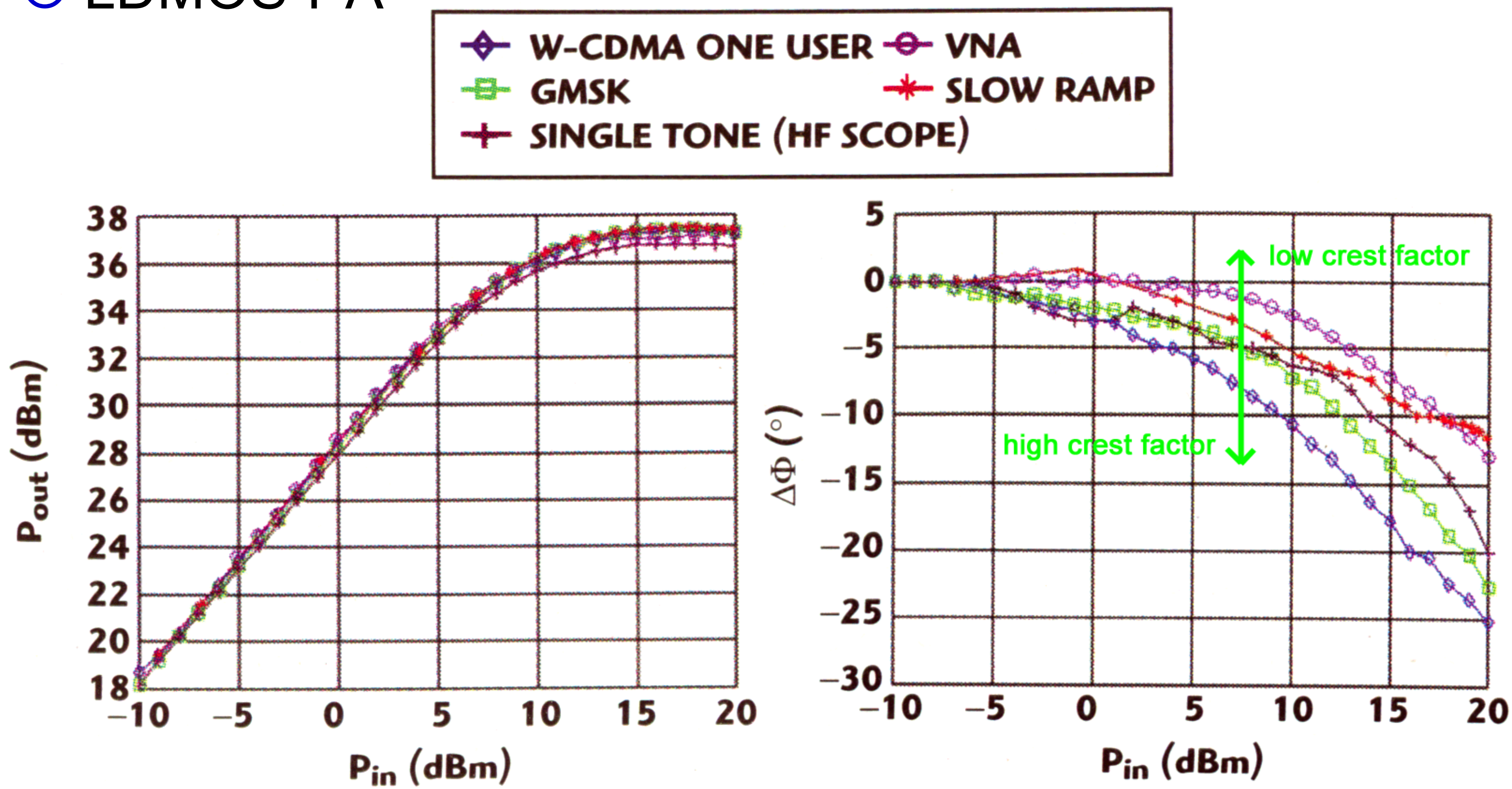
AM/AM- and AM/PM-Conversion

- GaAs-PA



AM/AM- and AM/PM-Conversion

- LDMOS-PA



How to preserve Linearity?

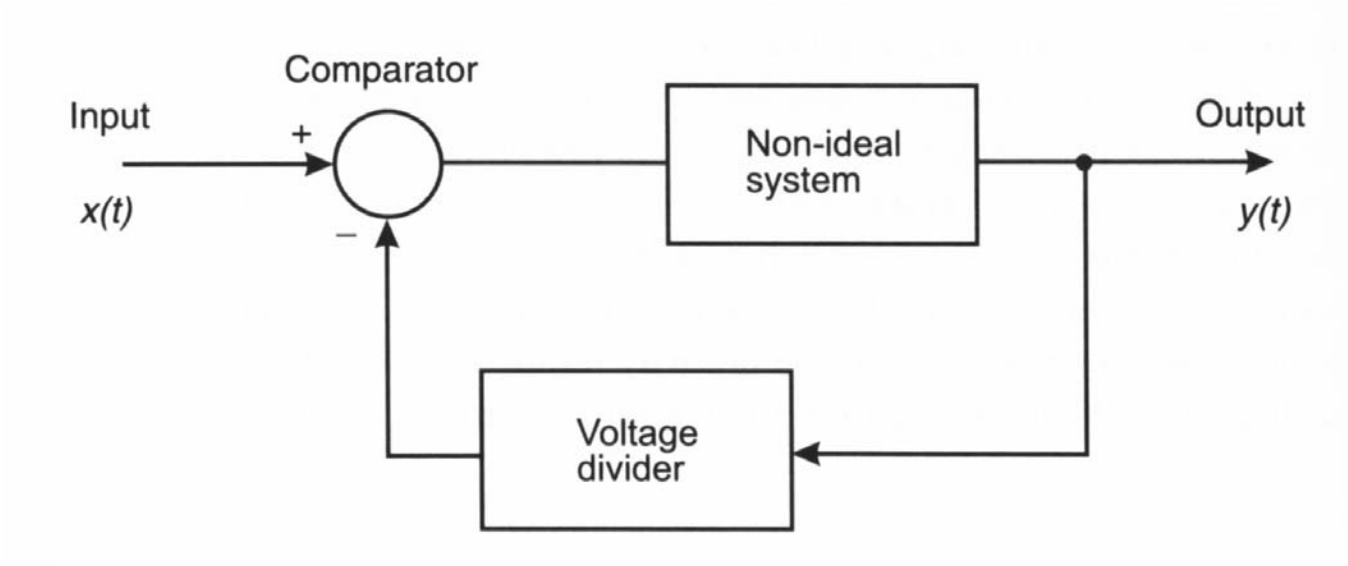
- Backed-Off Operation of PA
  - Simplest Way to achieve Linearity
- Linearity improving Concepts
  - Predistortion
  - Feedforward
  - ...

How to preserve Efficiency?

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

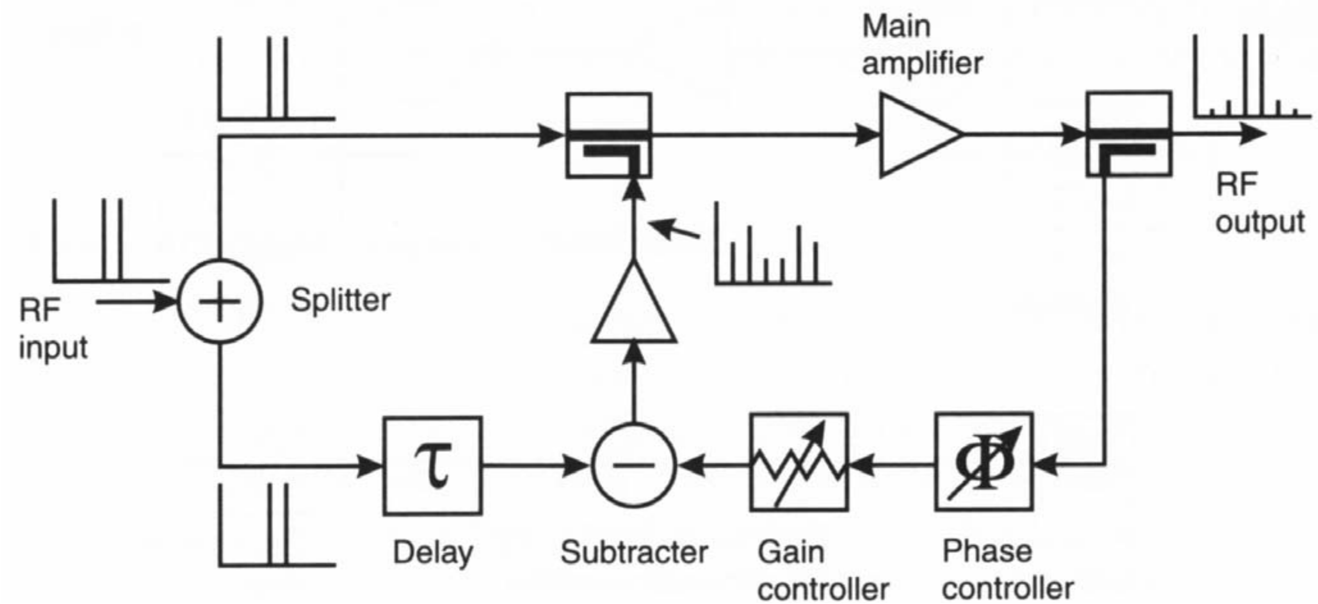
- Linearity improving Concepts
  - Higher Linearity at constant Efficiency
    → Higher Efficiency at constant Linearity

Direct (RF) Feedback



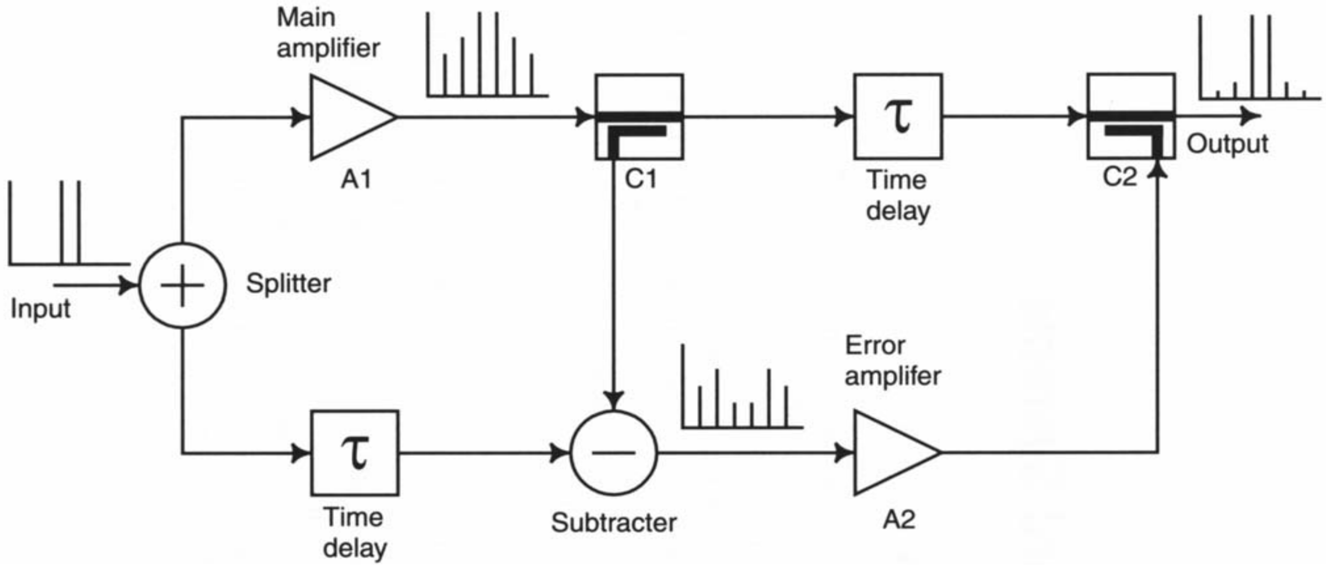
- Classical Method
- Decrease of Gain → Low Efficiency
- Feedback needs more Bandwidth than Signal
- Stability Problems at high Bandwidths

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

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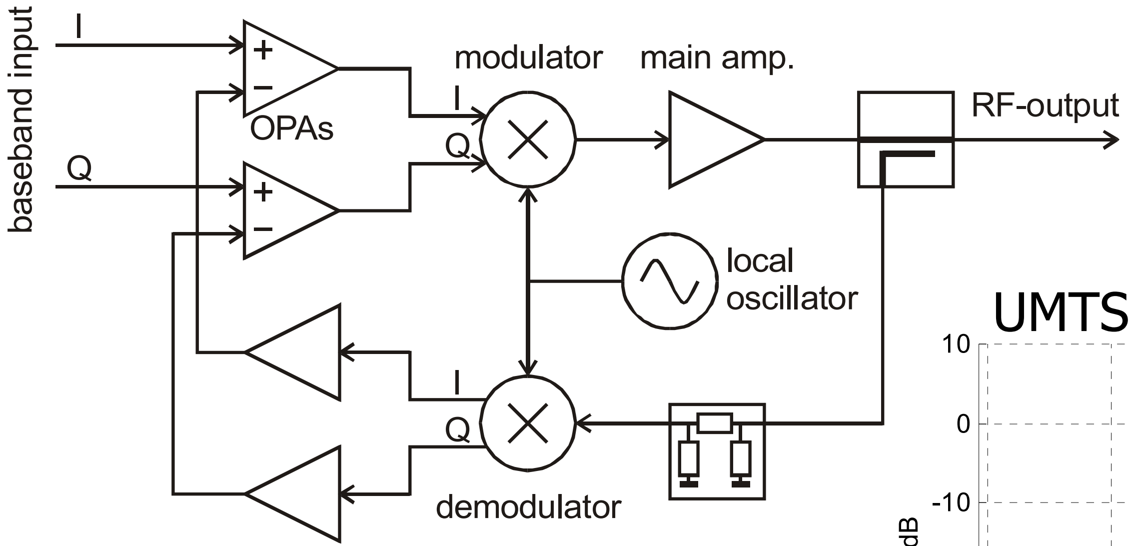
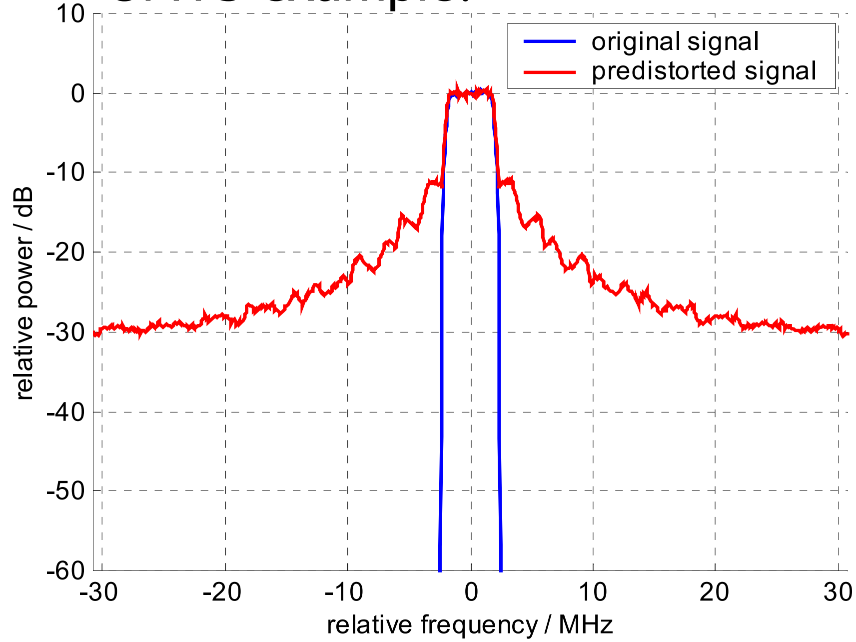
Cartesian Feedback



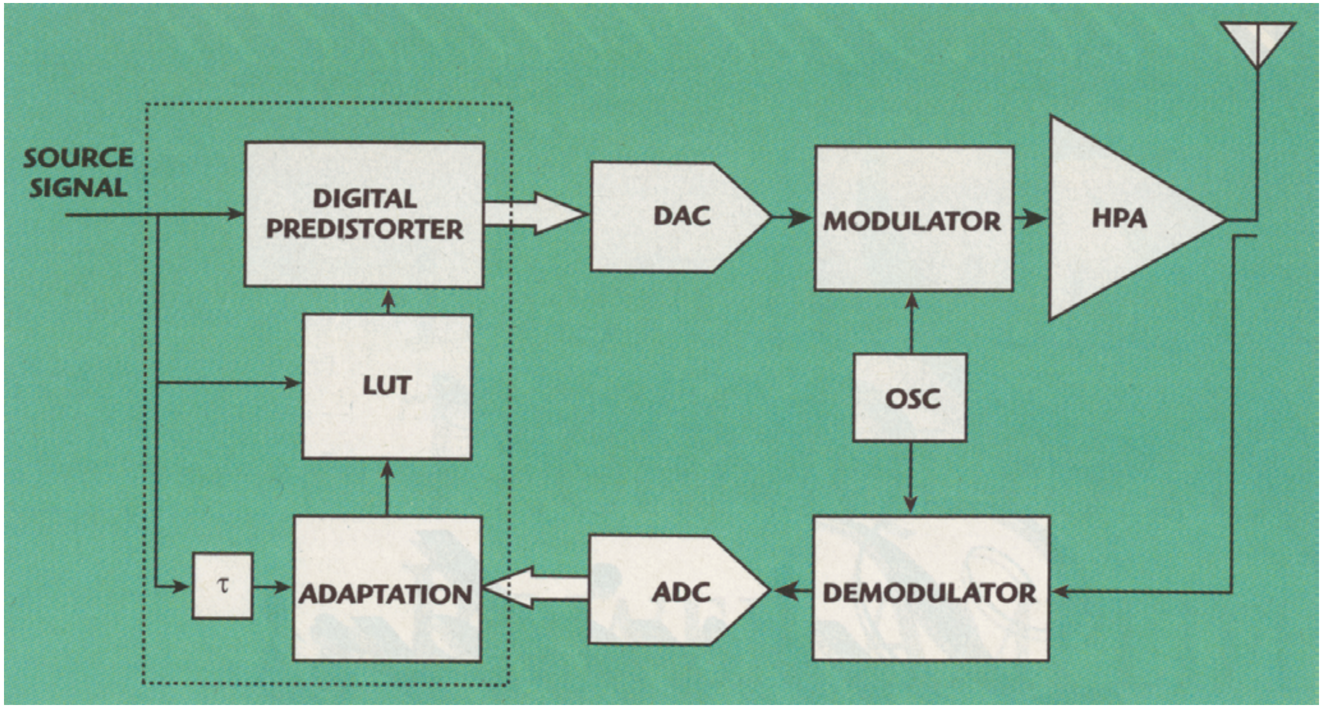
- AM/AM- and AM/PM-correction
- High Feedback-Bandwidth
- Stability Problems

UMTS example:



Digital Predistortion

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



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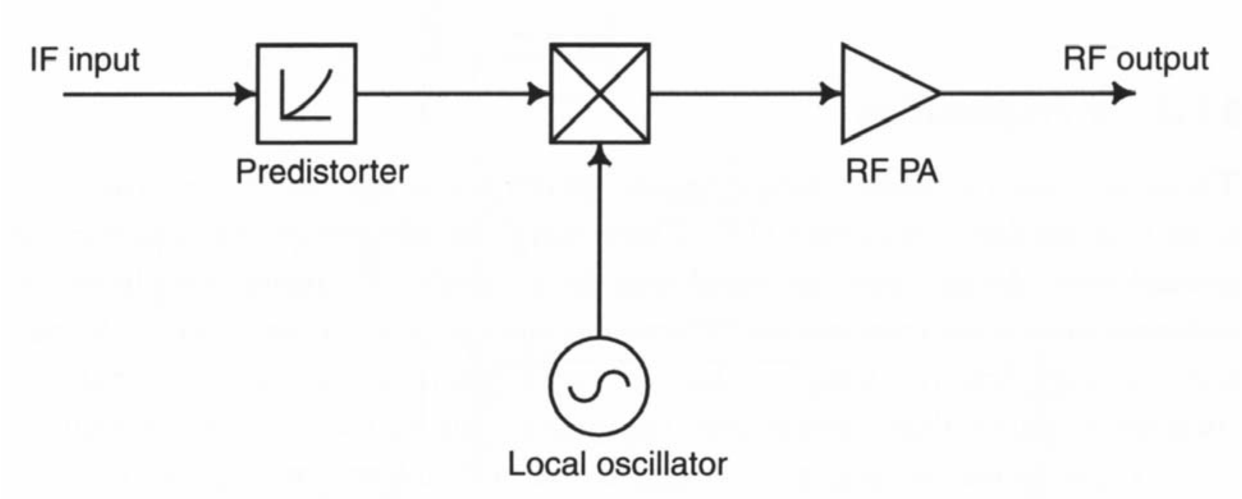
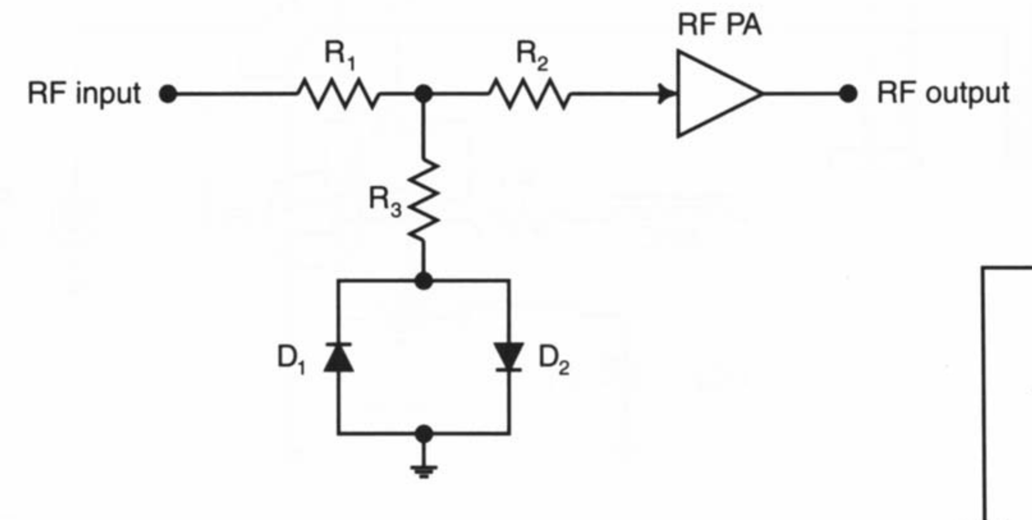
Analog Predistortion

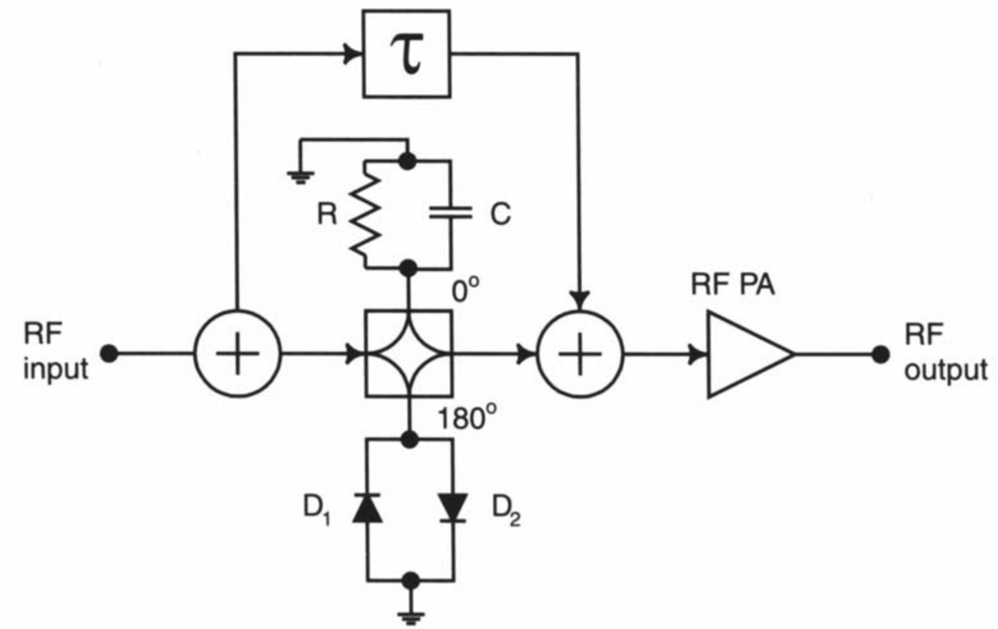


- Predistorter has inverse Function of Amplifier
- Leads to infinite Bandwidth (!)
- Hard to realize (accuracy)

Analog Predistortion

- Possible Realizations:





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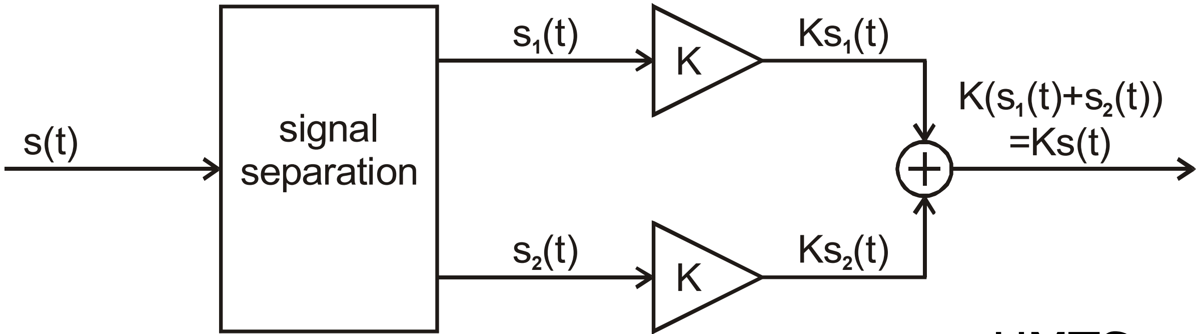
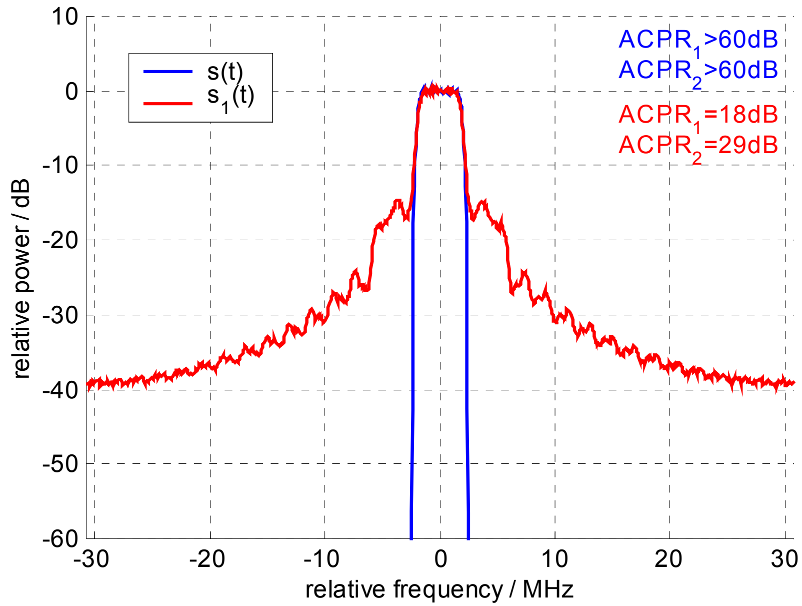
LINC (Linear Amplification by Nonlinear Components)



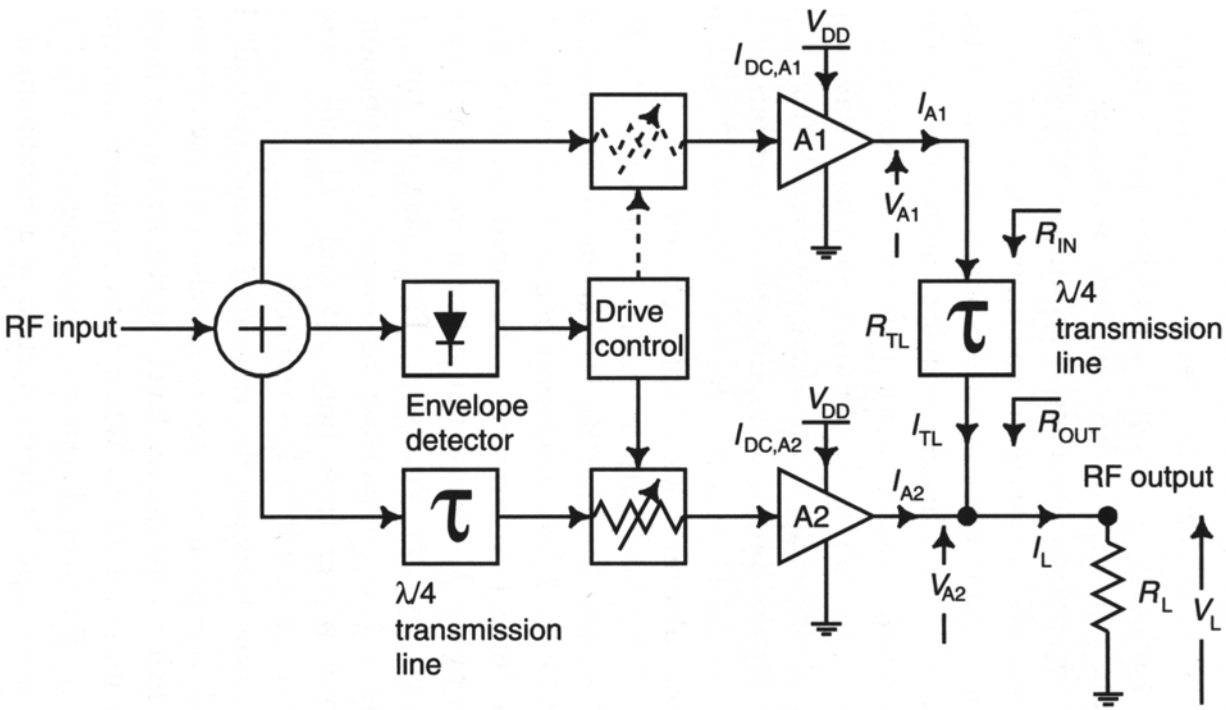
UMTS example:

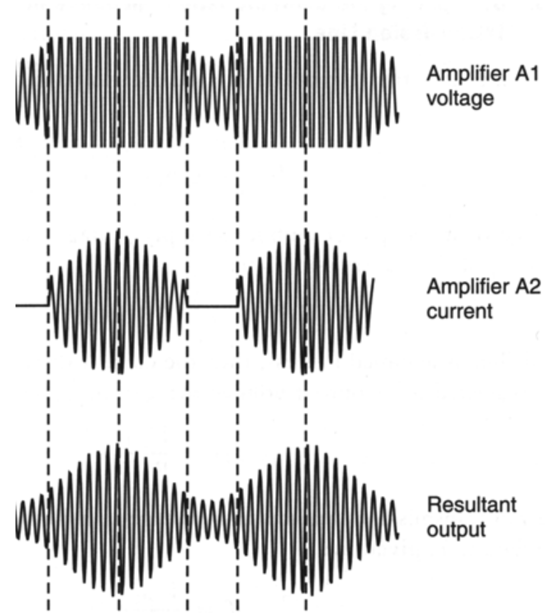


- AM/AM- and AM/PM-correction
- Digital separation required (accuracy!)
- High Bandwidth, oversampling necessary
- Stability guaranteed

Doherty Amplifier

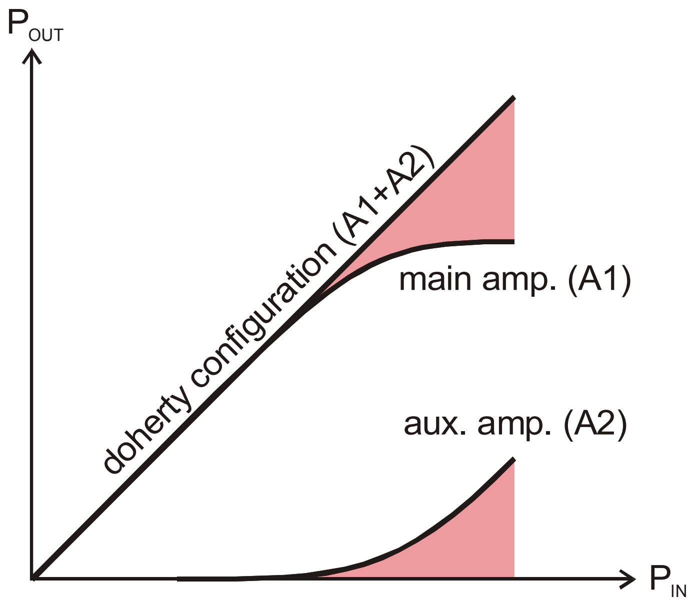
- Auxiliary amplifier supports main amplifier during saturation
- PAE can be kept high over a 6dB range



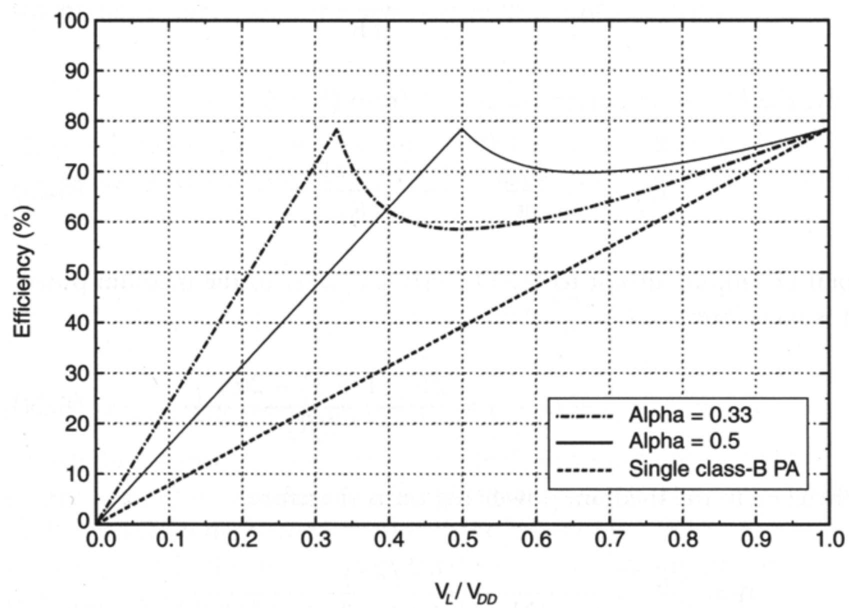


Doherty Amplifier

- Gain vs. Input Power



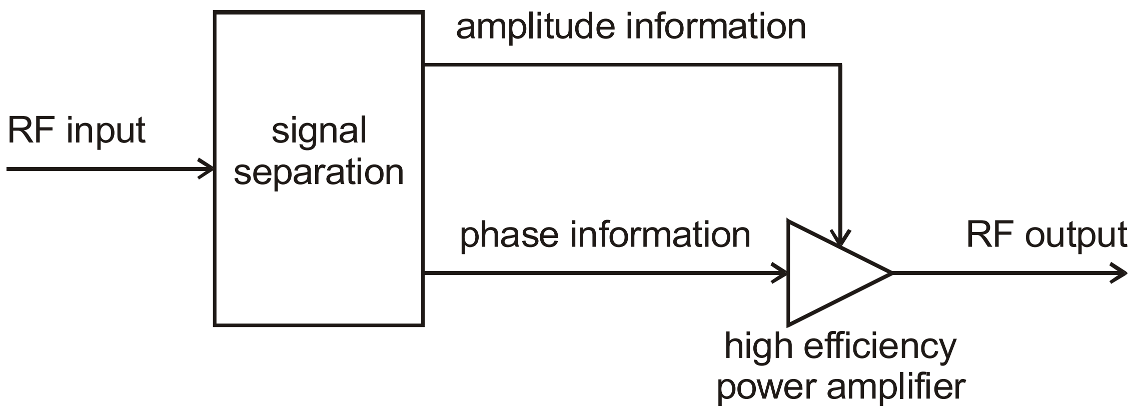
- Efficiency vs. Input Power



- No improvement of AM/AM- and AM/PM-distortion
- Behavior of auxiliary amplifier very hard (impossible) to realize
- Stability guaranteed

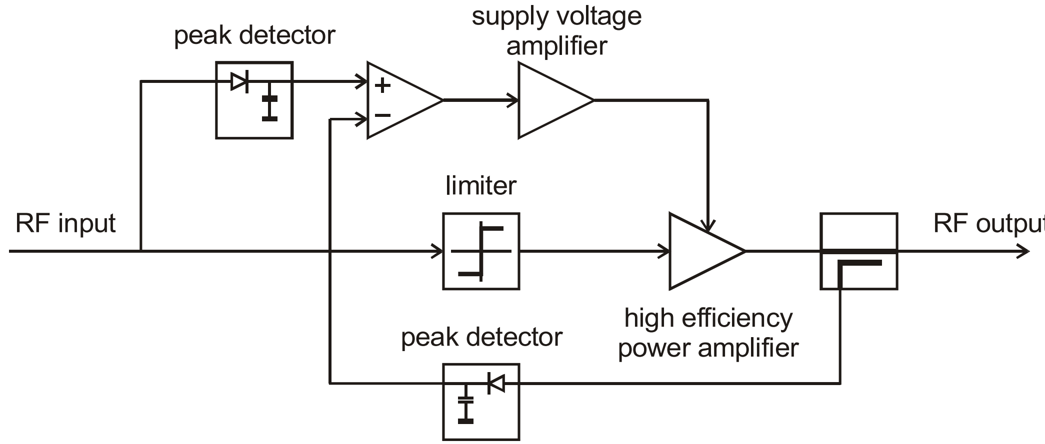
EER (Envelope Elimination and Restoration)

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

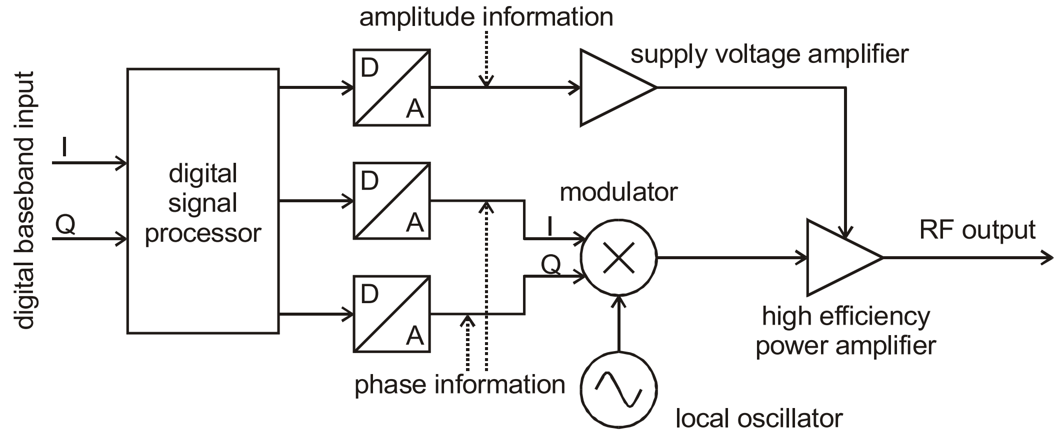


EER (Envelope Elimination and Restoration)

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



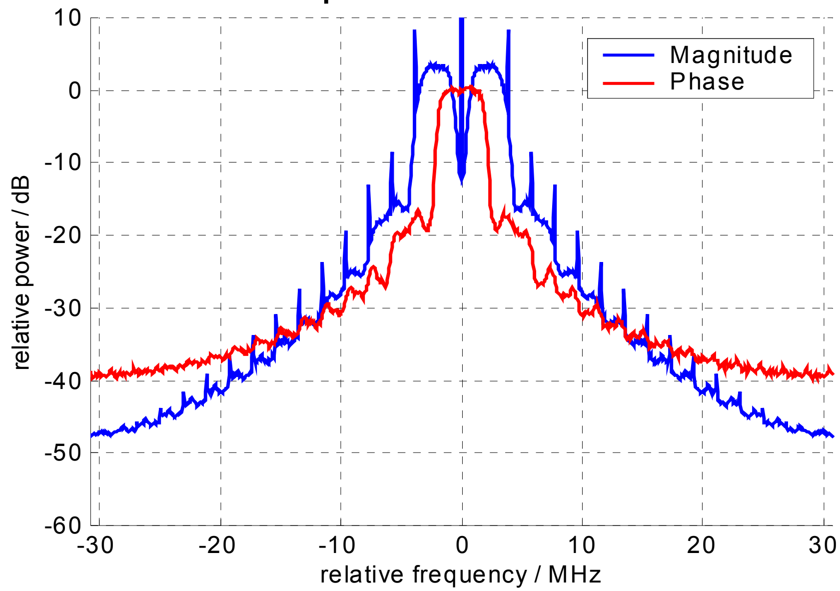
- Digital realization
  - Oversampling + high D/A-conversion rates required
  - High power consumption of DSP and D/A-converters
  - Possible feedback elimination
  - Compensation of AM/PM-distortion possible



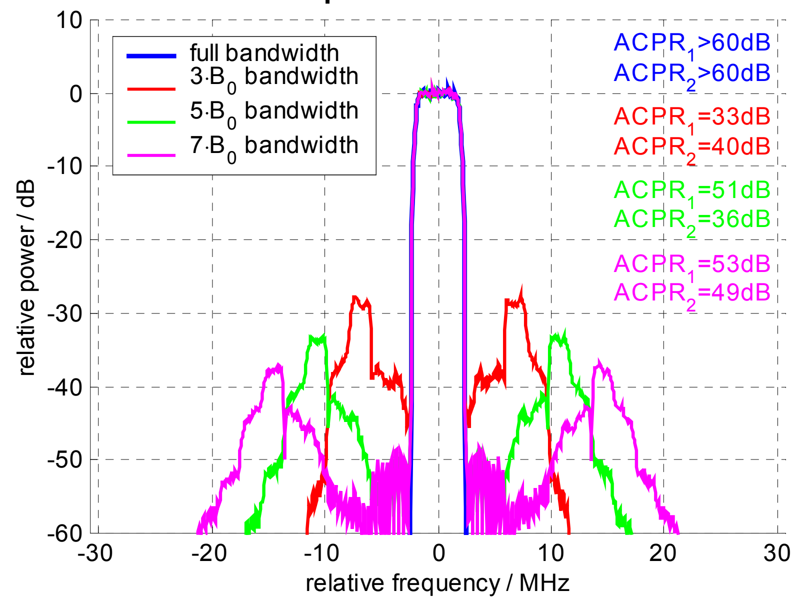
EER (Envelope Elimination and Restoration)

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

UMTS example:



UMTS example:



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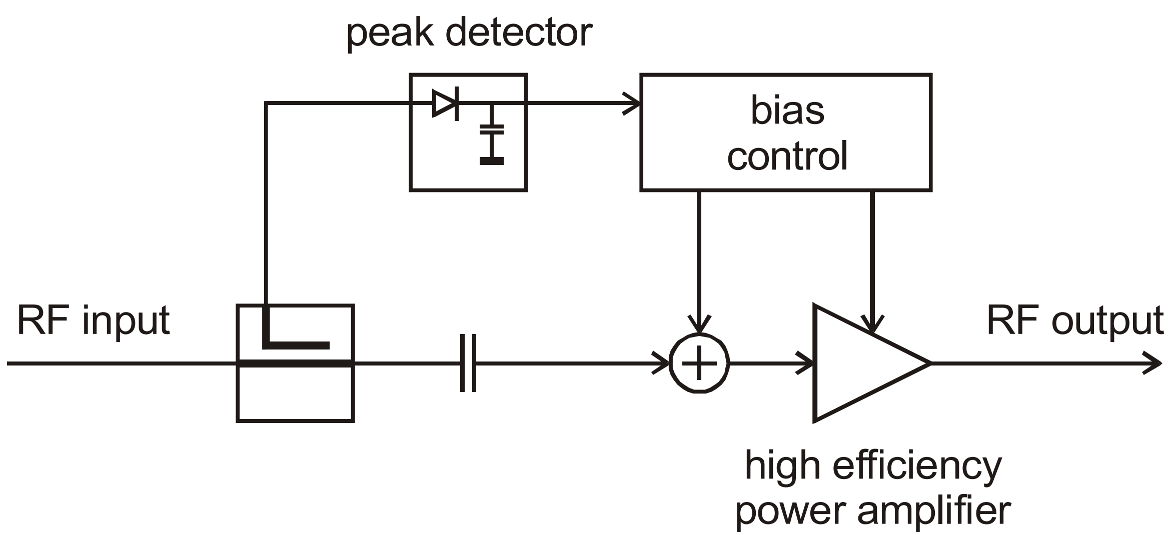
Adaptive Bias

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



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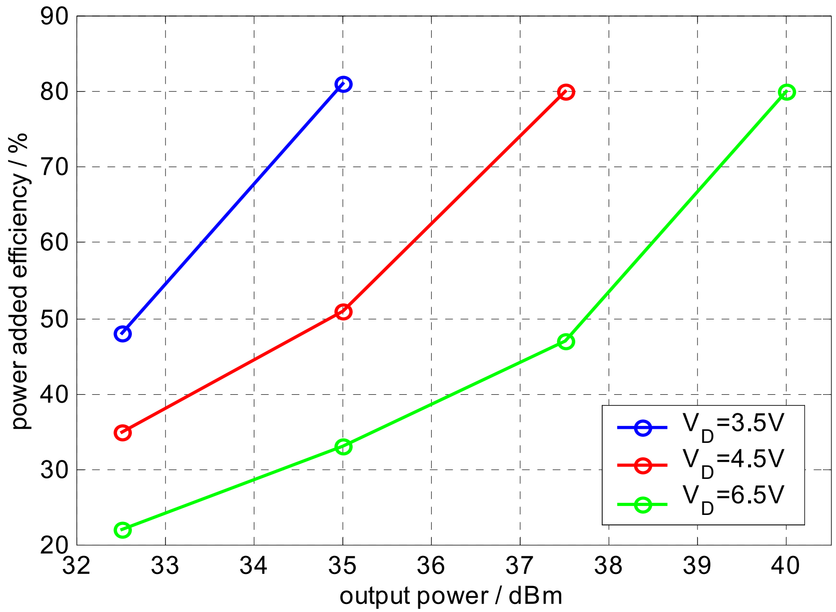
Adaptive Bias

- 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

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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

- F. Zavosh et al,
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  Artech House, 2000
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  "RF Power Amplifiers for Wireless Communications",
  Artech House, 1999

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