Behavioral Modeling and Digital Predistortion of Radio Frequency Power Amplifiers

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PhD Defense

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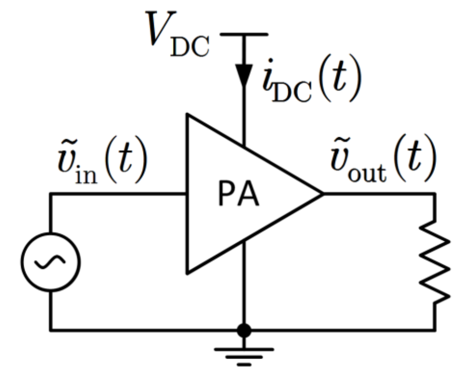
Overview

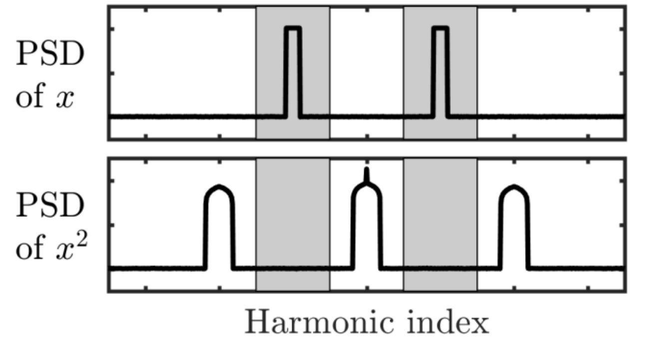
1. The linearity-efficiency trade-off

Joint linearity-efficiency model of
radio frequency power amplifiers (RF-PAs)



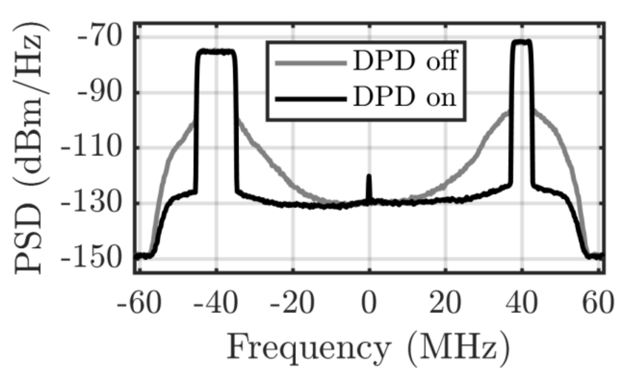
2. Behavioral modeling of RF-PAs

Even-order terms in
polynomial baseband models



3. Digital predistortion of RF-PAs

Dual-band digital predistortion (DPD) of an
envelope tracking power amplifier



The Linearity-Efficiency Trade-off

Motivation

$$\text{Linearity} \overset{\text{Joint model}}{\Longleftrightarrow} \text{Efficiency}$$

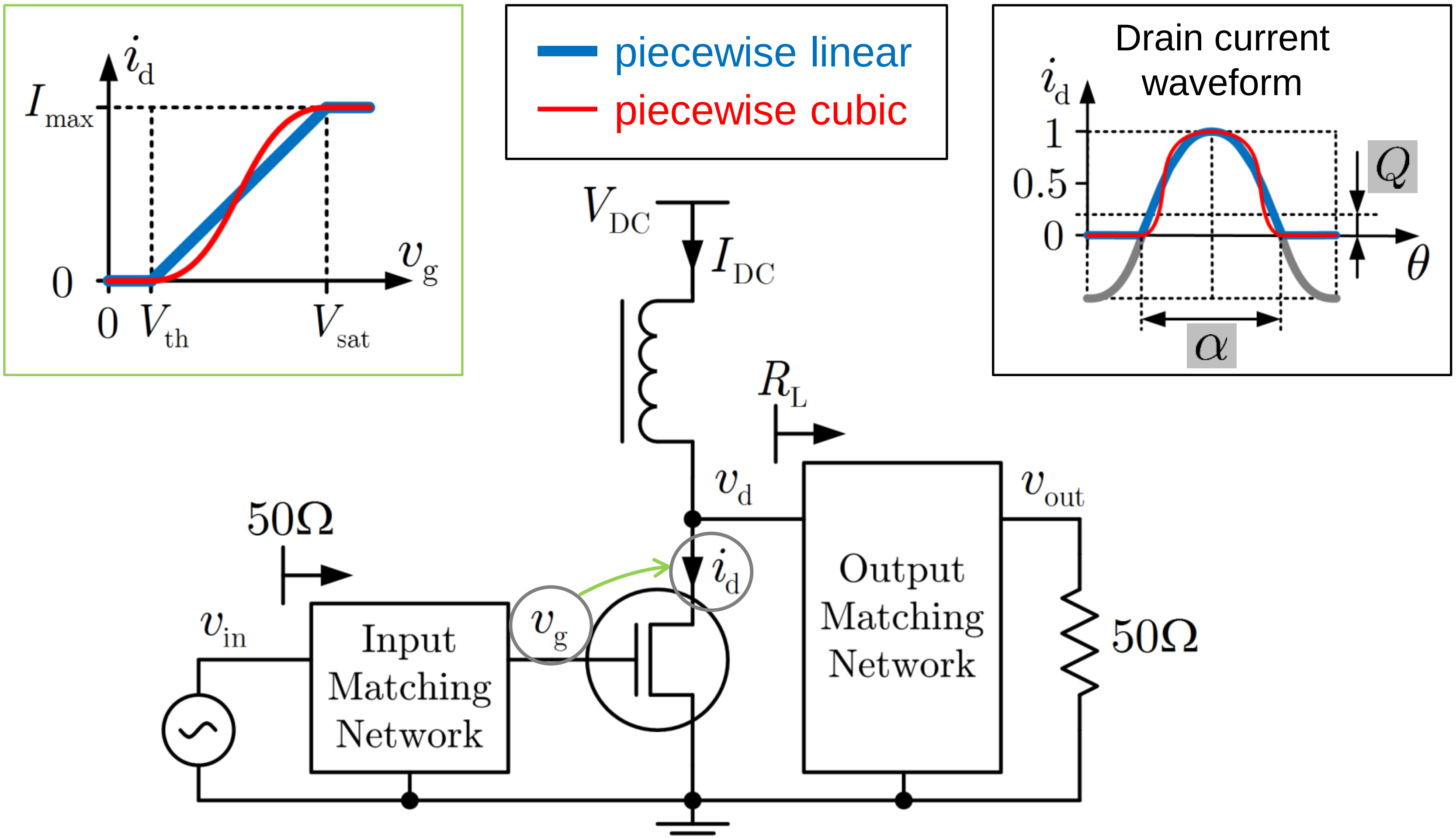
Research Question

What are the limitations of linearity and efficiency of RF-PAs?

Methodology

- Extend the classical efficiency analysis of RF-PAs
- Apply linearity and efficiency quantification methods
- Explore the linearity-efficiency trade-off by simulations

Circuit of a typical RF-PA

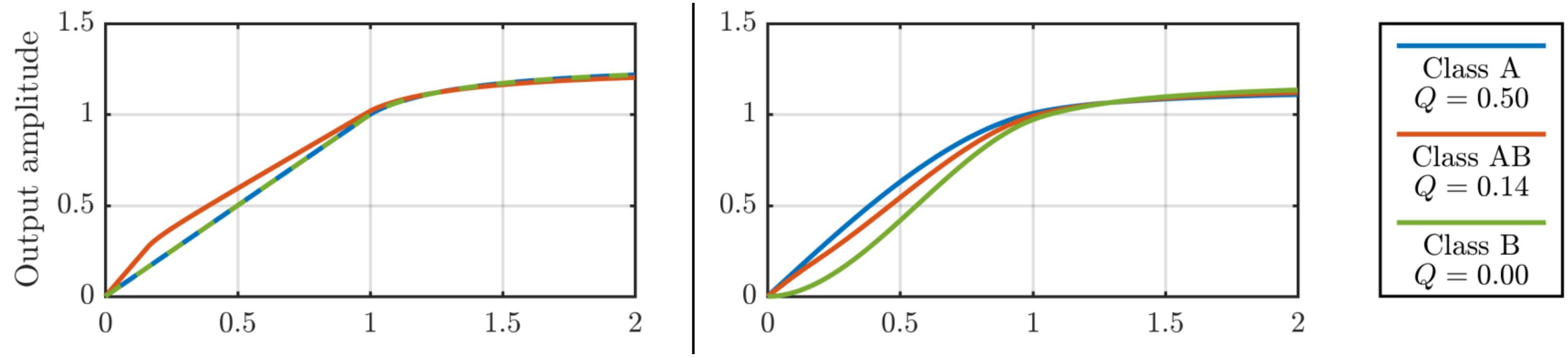


The **linearity** and **efficiency** characteristics can be derived by a **Fourier series analysis** of the **drain current waveform**.

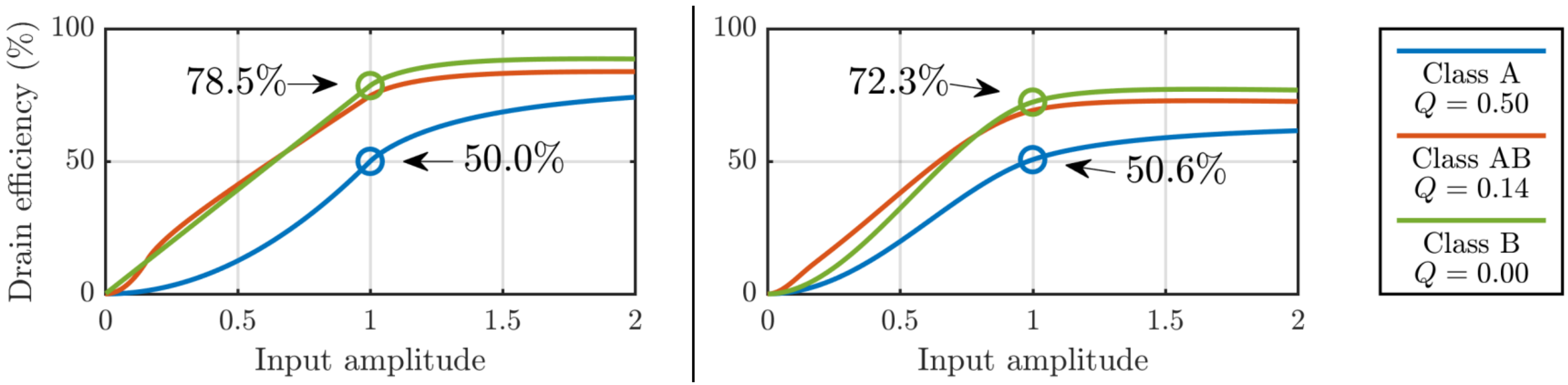
Linearity & Efficiency Behavior

Piecewise linear transistor model | **Piecewise cubic** transistor model

Linearity: Amplitude modulation to amplitude modulation (AM-AM)



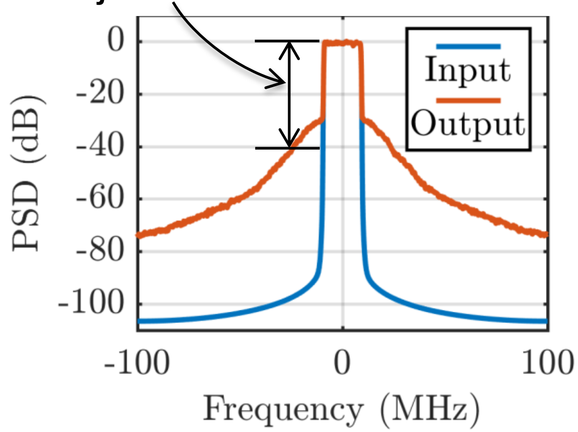
Efficiency: Instantaneous drain efficiency



The **piecewise cubic** transistor model produces realistic **linearity** and **efficiency** characteristics.

Linearity & Efficiency Evaluation

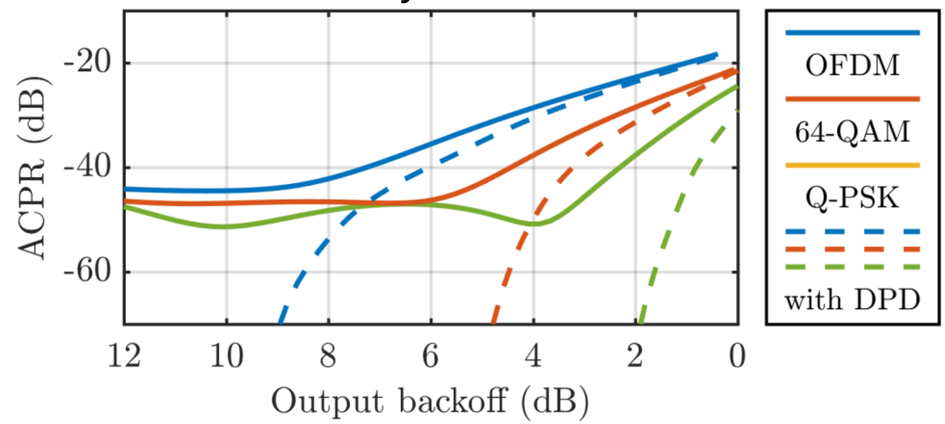
Adjacent **C**hannel **P**ower **R**atio



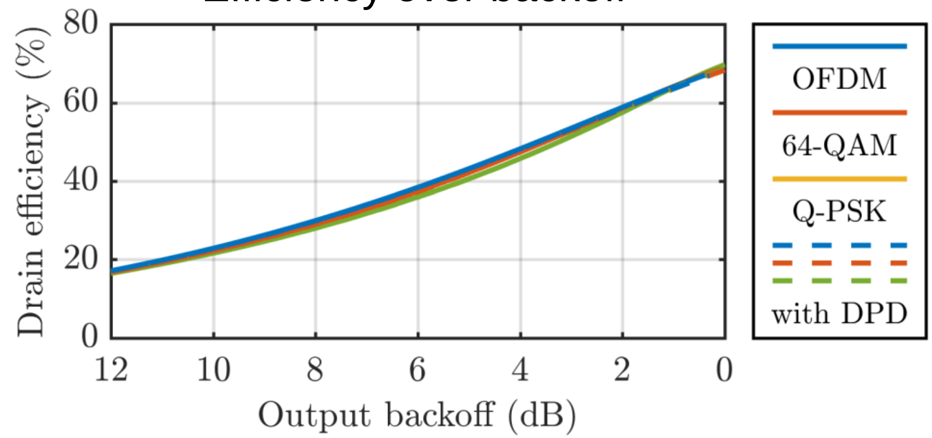
Average drain efficiency

$$\eta_{\text{drain,avg}} = \frac{\mathbb{E}\{P_{\text{RF}}\}}{\mathbb{E}\{P_{\text{DC}}\}}$$

Nonlinearity over backoff



Efficiency over backoff



Nonlinearity metrics strongly depend on the **signal statistics**.
Average drain efficiency mainly depends on the **output power backoff**.

Behavioral Modeling of RF-PAs

Motivation

Conventional theory:	Only **odd-order** terms in RF-PA baseband models
Experimental evidence:	**Even-order** terms can improve the accuracy

Research Question

What are the foundations of complex baseband models of RF-PAs?

Methodology

- Derive passband-baseband model pairs with even-order terms
- Analyze the mathematical properties of complex baseband models

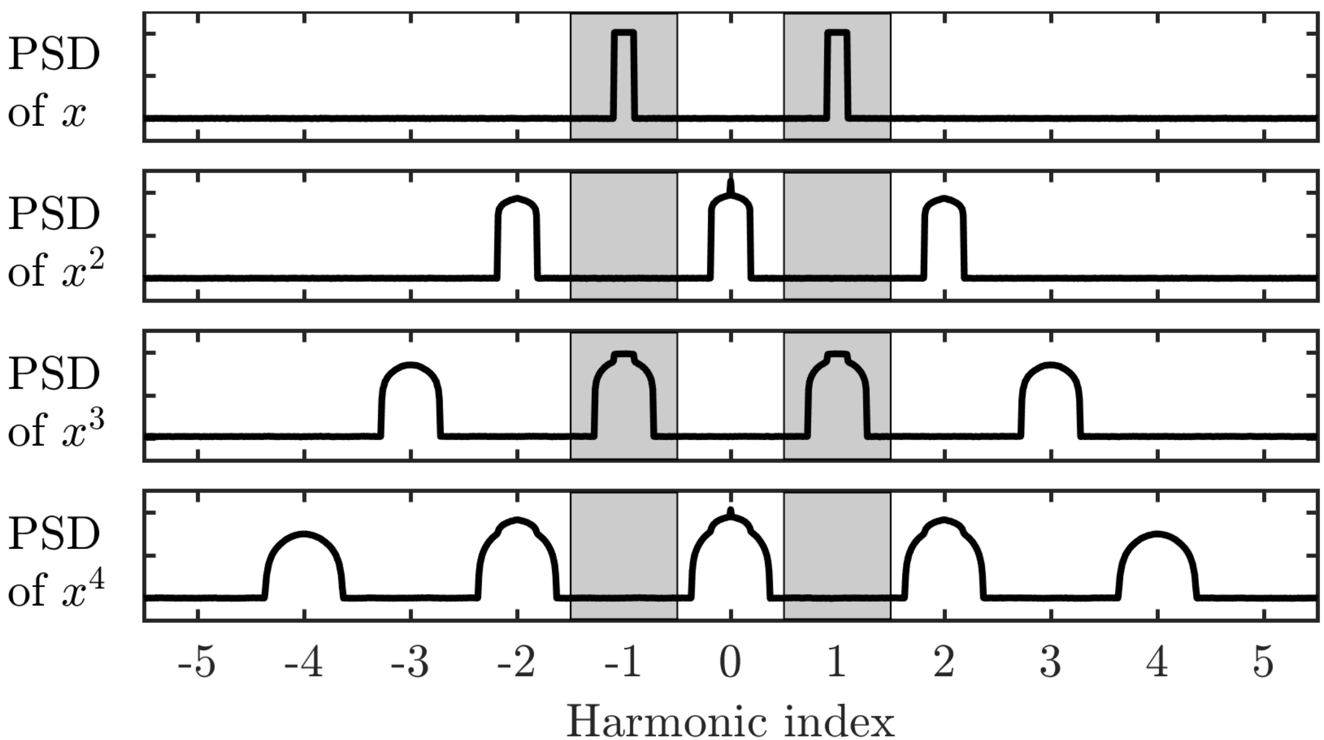
Spectral Analysis of a Polynomial Model

Passband signal

$$x(t) = \mathrm{Re}\{\tilde{x}(t)\, e^{\mathrm{j}\omega t}\}$$

Passband model

$$y(t) = \sum_{p=1}^{P} \alpha_p\, x^p(t)$$



Only **odd-order** monomials produce output in the **first spectral zone**.

Analysis of Even-Order Terms

Passband model

$$y(t) = \sum_{p=1}^{P} \alpha_p \, x^p(t)$$

Polynomial basis functions

Chebyshev transform [1]

Baseband model

$$\tilde{y}(t) = \sum_{\substack{p=1 \\ p \text{ is odd}}}^{P} \tilde{\alpha}_p \, \tilde{x}(t) \left|\tilde{x}(t)\right|^{p-1}$$

Include even-order terms

$$\tilde{y}(t) = \sum_{p=1}^{P} \tilde{\alpha}_p \, \tilde{x}(t) \left|\tilde{x}(t)\right|^{p-1}$$

Inverse Chebyshev transform [1]

$$y(t) = \sum_{p=1}^{P} \alpha_p \, x(t) \left|x(t)\right|^{p-1}$$

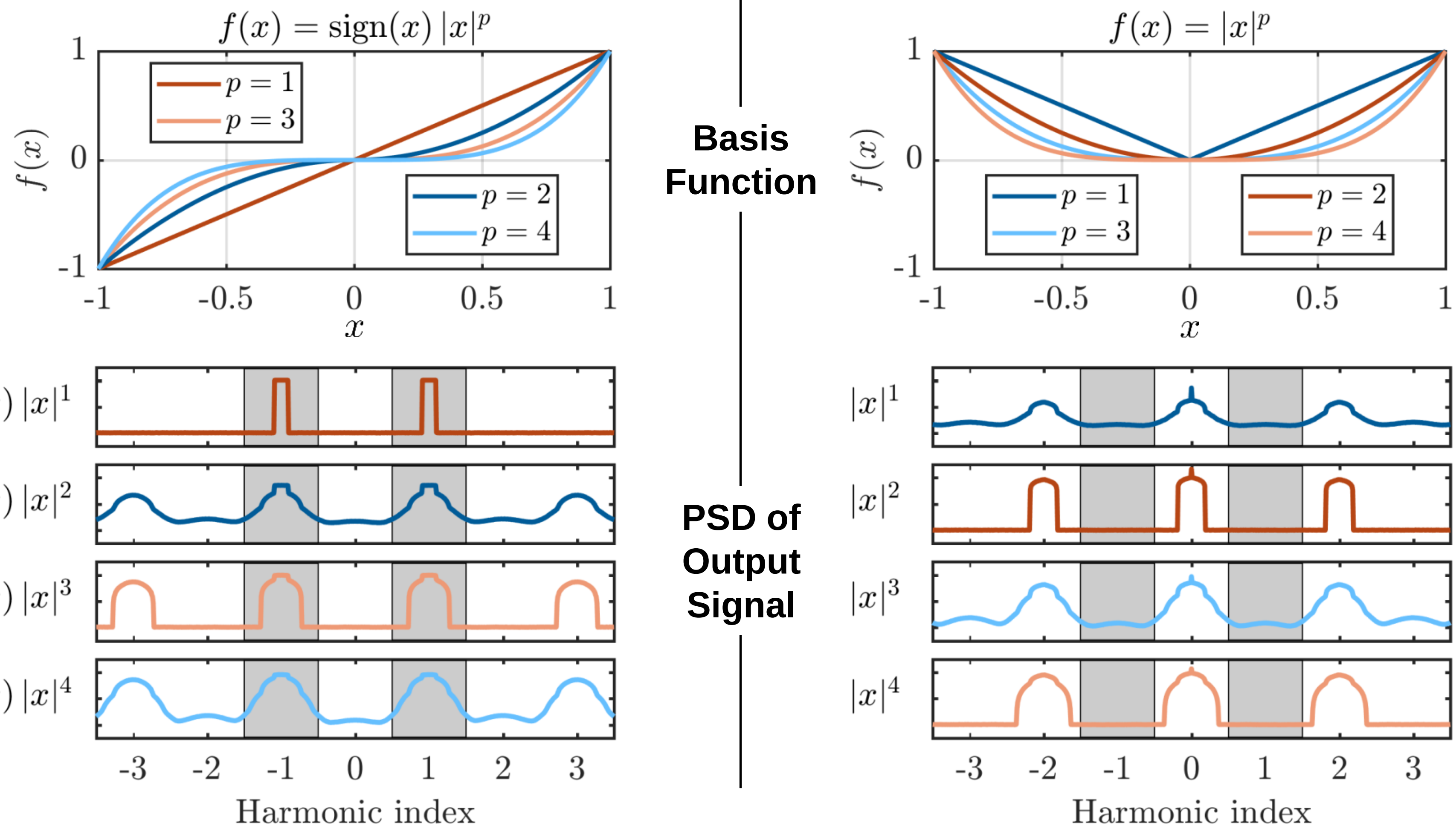
Odd-symmetric magnitude-power functions

Even-order terms in the **baseband model** can be explained by **odd-symmetric magnitude-power** functions in the **passband model**.

[1] N. Blachman, "Detectors, bandpass nonlinearities, and their optimization: Inversion of the Chebyshev transform", *IEEE Transactions on Information Theory*, volume 17, number 4, pages 398–404, July 1971.

Magnitude Power Functions

Odd-symmetric | **Even-symmetric**



Spectral characteristics correlate with **symmetry** of basis functions, not with **order**.

Polynomial Models with Memory

Volterra series

$$y(t) = \sum_{p=1}^{P} \int_{\mathbb{R}^p} h_p(\boldsymbol{\tau}_p)\, \Psi_p(t, \boldsymbol{\tau}_p)\, \mathrm{d}\boldsymbol{\tau}_p$$

Basis functionals

Passband

Baseband $q = \lfloor (p+1)/2 \rfloor$

$$\underbrace{\prod_{i=1}^{p} x(t-\tau_i)}_{p\text{-fold product}}$$

Transform[1]

$$\underbrace{\underbrace{\prod_{i=1}^{q} \tilde{x}(t-\tau_i)}_{q \text{ terms}} \underbrace{\prod_{l=q+1}^{2q-1} \tilde{x}^*(t-\tau_i)}_{(q-1) \text{ terms}}}_{p\text{-fold product, } p \text{ is odd}}$$

$$\underbrace{\underbrace{\prod_{i=1}^{p-1} x(t-\tau_i)}_{(p-1) \text{ terms}} \underbrace{|x(t-\tau_p)|}_{1 \text{ term}}}_{p\text{-fold product, } p \text{ is even}}$$

Transform and prune

$$\underbrace{\underbrace{\prod_{i=1}^{q} \tilde{x}(t-\tau_i)}_{q \text{ terms}} \underbrace{\prod_{l=q+1}^{2q-1} \tilde{x}^*(t-\tau_i)}_{(q-1) \text{ terms}} \underbrace{|x(t-\tau_p)|}_{1 \text{ term}}}_{p\text{-fold product, } p \text{ is even}}$$

Even-order terms in **baseband** can also be derived for **Volterra** series models.

[1] S. Benedetto, E. Biglieri, and R. Daffara, “Modeling and performance evaluation of nonlinear satellite links – A Volterra series approach”, *IEEE Transactions on Aerospace and Electronic Systems*, volume 15, number 4, pages 494–507, July 1979.

Phase Homogeneity

Passband model

$$\mathcal{N} \quad : \quad x(t) \quad \mapsto \quad y(t)$$

Baseband model

$$\tilde{\mathcal{N}}_k \quad : \quad \tilde{x}(t) \quad \mapsto \quad \tilde{y}_k(t)$$

If the passband model is **time-invariant**, the baseband model must obey **phase homogeneity**:

$$\boxed{\tilde{\mathcal{N}}_k\Big\{e^{\mathrm{j}\xi}\,\tilde{x}(t)\Big\} = e^{\mathrm{j}k\xi}\,\tilde{\mathcal{N}}_k\Big\{\tilde{x}(t)\Big\}}$$

e.g. baseband Volterra series (1st harmonic, k=1)

1st Order	$\tilde{x}(t-\tau_1)$				
2nd Order	$\tilde{x}(t-\tau_1)$	$\lvert\tilde{x}(t-\tau_2)\rvert$			
3rd Order	$\tilde{x}(t-\tau_1)$	$\tilde{x}(t-\tau_2)$	$\tilde{x}^*(t-\tau_3)$		
4th Order	$\tilde{x}(t-\tau_1)$	$\tilde{x}(t-\tau_2)$	$\tilde{x}^*(t-\tau_3)$	$\lvert\tilde{x}(t-\tau_4)\rvert$	
5th Order	$\tilde{x}(t-\tau_1)$	$\tilde{x}(t-\tau_2)$	$\tilde{x}(t-\tau_3)$	$\tilde{x}^*(t-\tau_4)$	$\tilde{x}^*(t-\tau_5)$

Phase homogeneity is a **necessary symmetry** of all **complex baseband** models of **time-invariant passband** systems.

Digital Predistortion of RF-PAs

Motivation

Improve the performance of a practical wireless transmitter

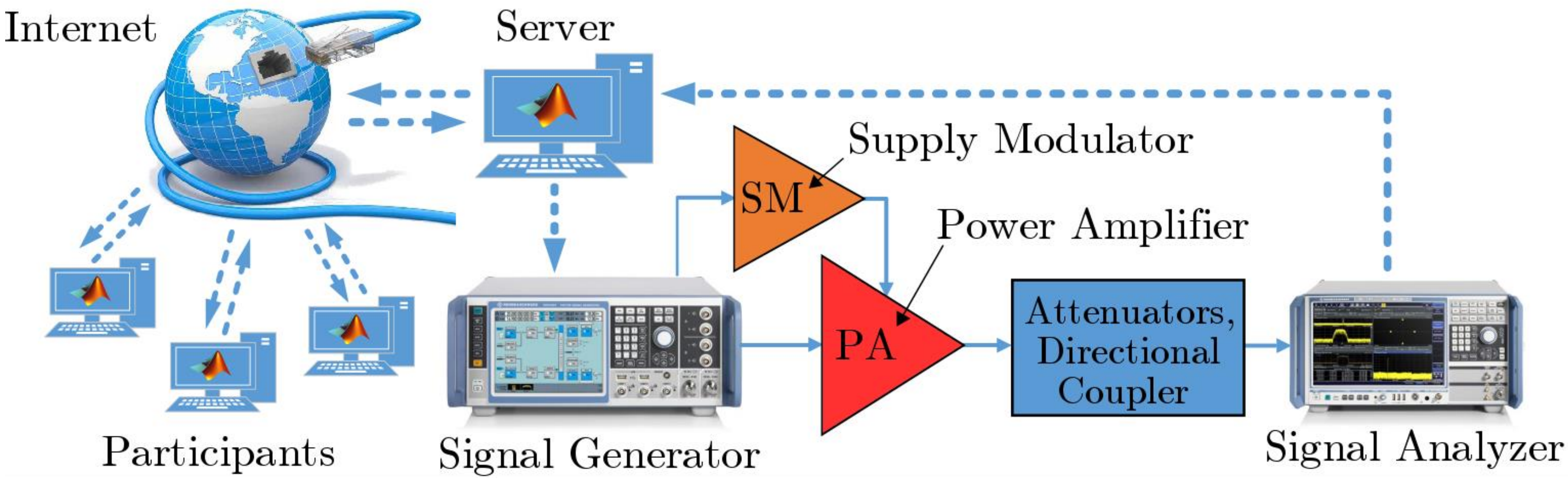
Research Question

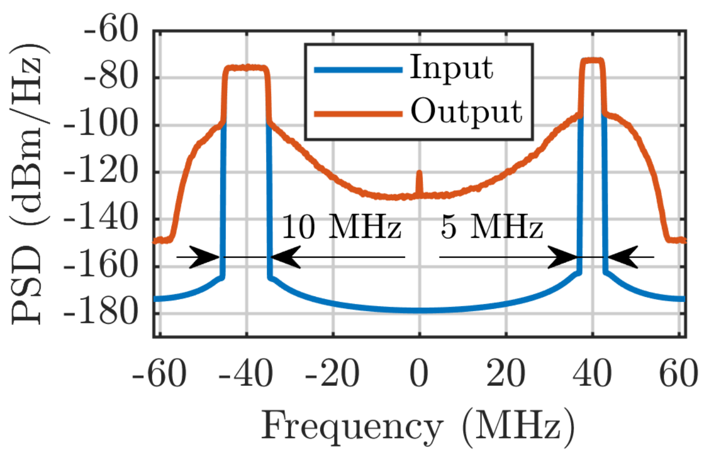
Which methods give the best results in practical DPD applications?

Methodology

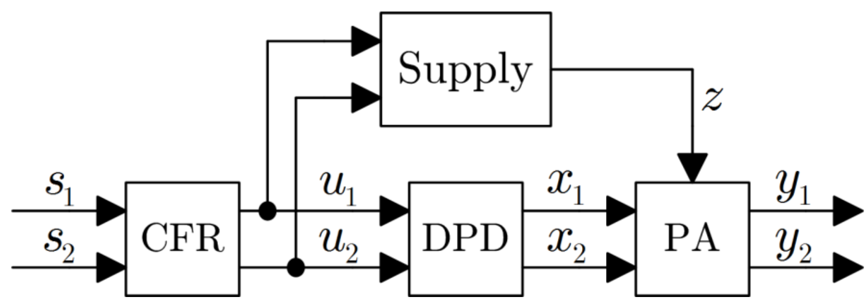
- Student design competition “PA linearization through DPD”
- Remote measurement setup
- Benchmarking of DPD methods

Setup of DPD Design Competition 2017



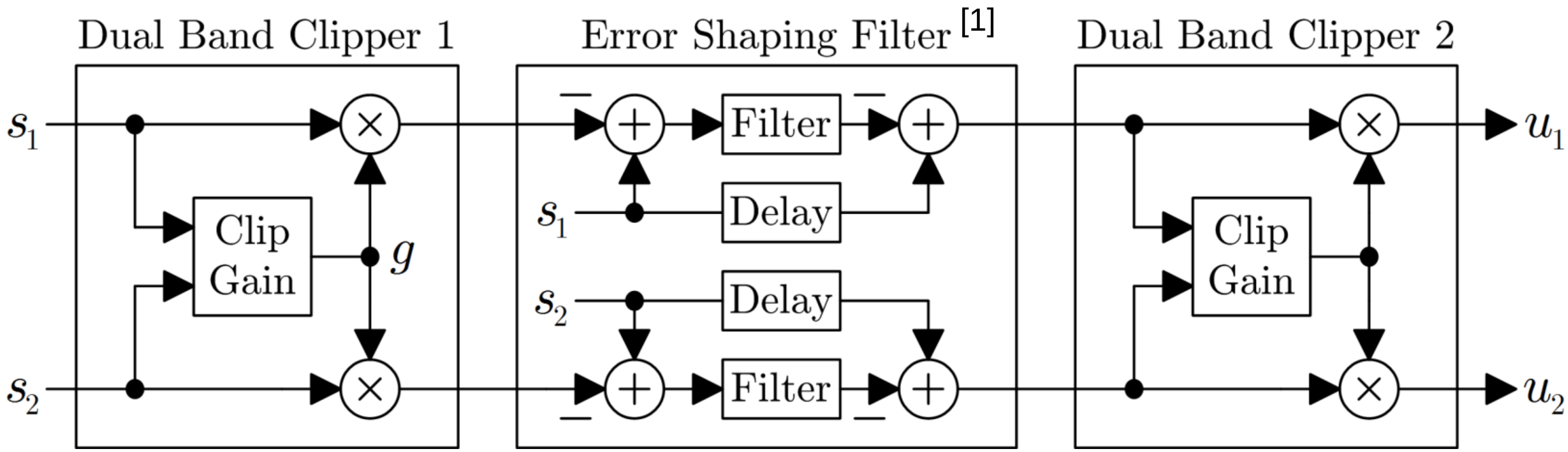


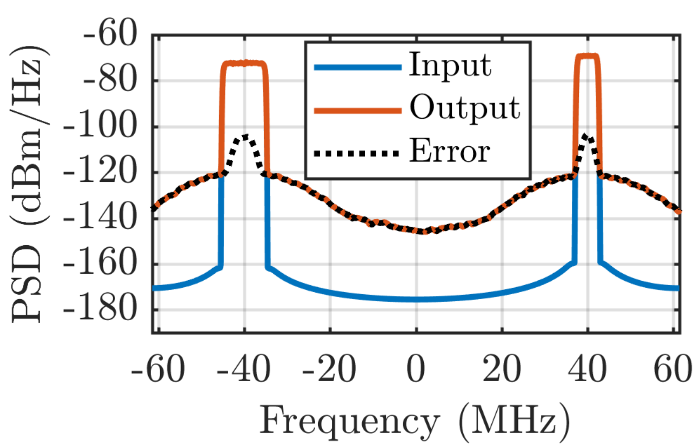
Linearization architecture:

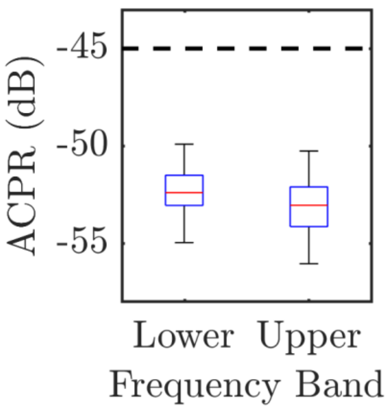


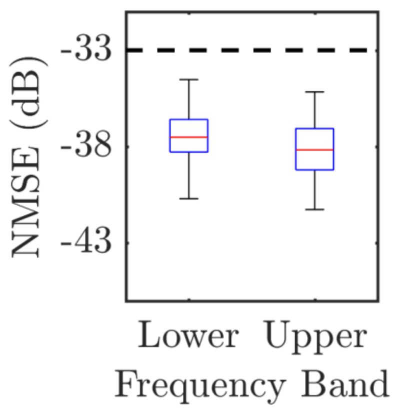
Aim: Produce the highest **output power** for given **linearity requirements**.

Crest Factor Reduction









Final crest factor

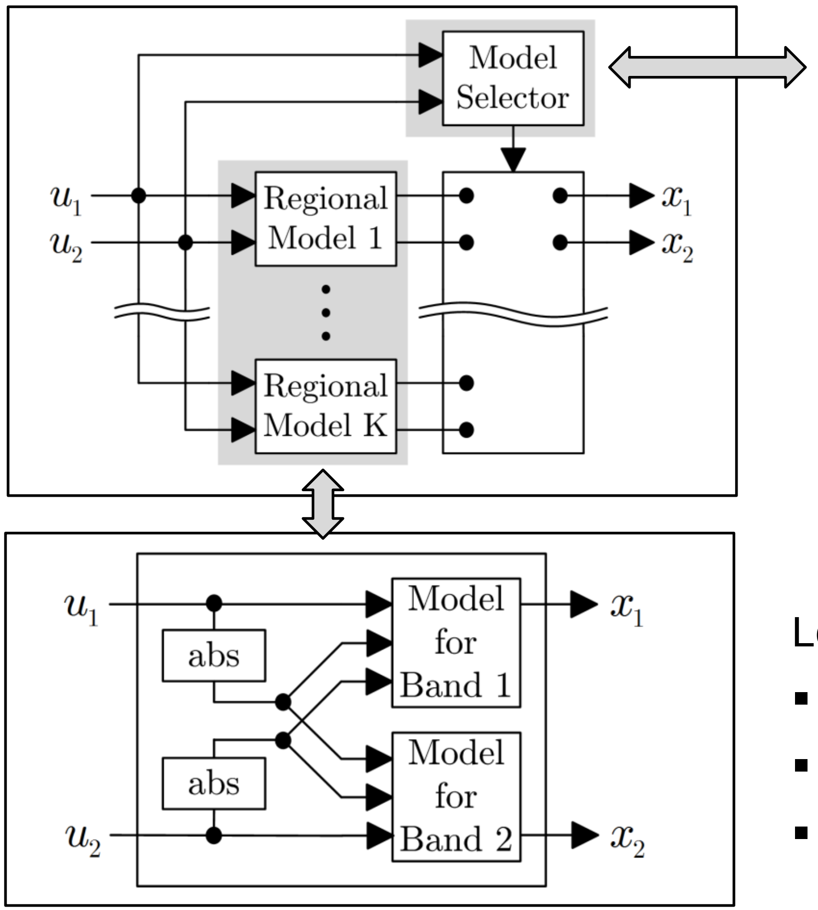
8.6 dB

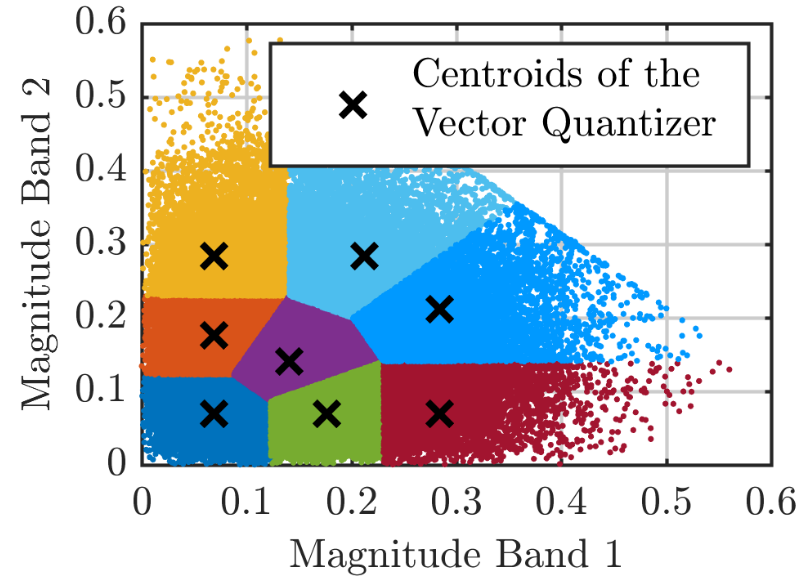
Crest factor reduction simplifies the linearization by **digital predistortion**.

[1] W.-J. Kim, K.-J. Cho, S. P. Stapleton, and J.-H. Kim, “An efficient crest factor reduction technique for wideband applications”, *Analog Integrated Circuits and Signal Processing*, volume 51, number 1, pages 19–26, April 2007.

Structure of the Digital Predistorter

Dual-band vector-switched[1] model





Low-level model structure

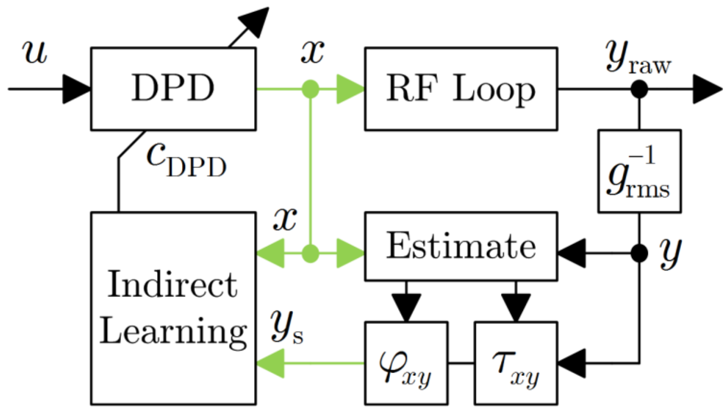
- Pruned generalized memory polynomial
- Pruned dual-band memory polynomial
- 72 coefficients per region and band

Piecewise models: higher **accuracy** by higher **locality**.

[1] S. Afsardoost, T. Eriksson, and C. Fager, “Digital Predistortion Using a Vector-Switched Model”, *IEEE Transactions on Microwave Theory and Techniques*, volume 60, number 4, pages 1166–1174, April 2012.

Training of the Digital Predistorter

Indirect learning

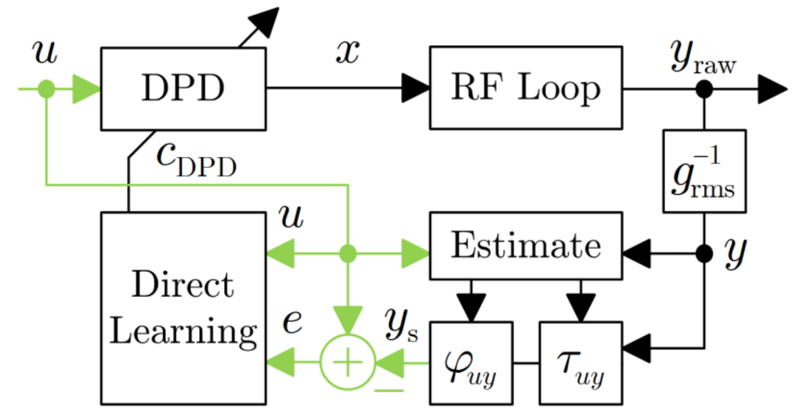


Inverse mapping
$y_\mathrm{s} \mapsto x$

$$\boldsymbol{x} = \boldsymbol{Y}_\mathrm{s}\,\boldsymbol{c}_\mathrm{DPD}$$

$$\begin{bmatrix} x[1] \\ \vdots \\ x[N] \end{bmatrix} = \begin{bmatrix} \mathcal{F}_1\{y_\mathrm{s}[1]\} & \dots & \mathcal{F}_K\{y_\mathrm{s}[1]\} \\ \vdots & \vdots & \vdots \\ \mathcal{F}_1\{y_\mathrm{s}[N]\} & \dots & \mathcal{F}_K\{y_\mathrm{s}[N]\} \end{bmatrix} \begin{bmatrix} c_{1,\mathrm{DPD}} \\ \vdots \\ c_{K,\mathrm{DPD}} \end{bmatrix}$$

Direct learning [1]



Error mapping
$u \mapsto e$

$$\boldsymbol{e} = \boldsymbol{U}\,\boldsymbol{c}_\mathrm{error}$$

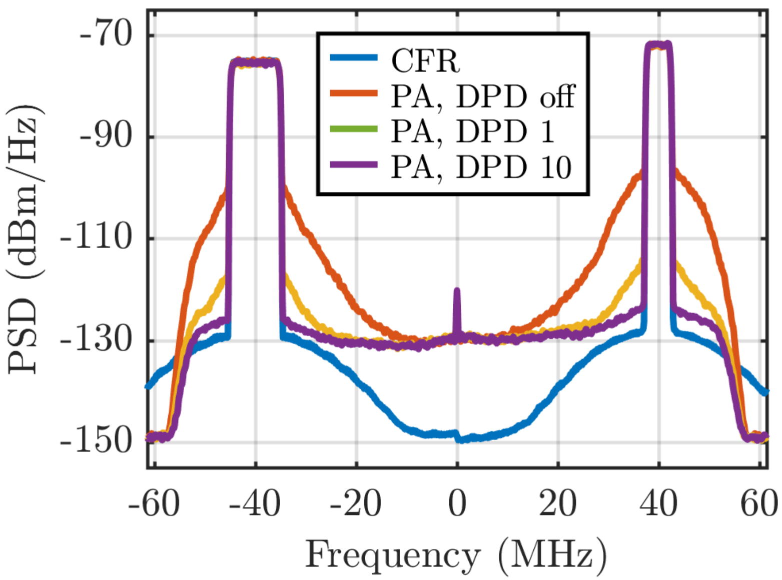
Iterative coefficient update

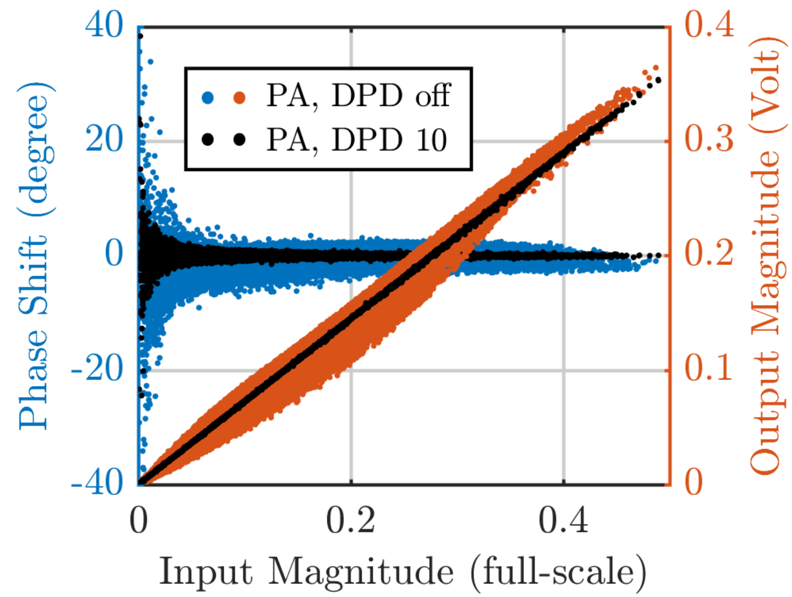
$$\boldsymbol{c}_\mathrm{DPD}^{(i+1)} = \boldsymbol{c}_\mathrm{DPD}^{(i)} + \mu\,\boldsymbol{c}_\mathrm{error}^{(i)}$$

Initialize with **indirect learning**, optimize with several iterations of **direct learning**.

[1] L. Guan and A. Zhu, “Dual-loop model extraction for digital predistortion of wideband RF power amplifiers”, *IEEE Microwave and Wireless Components Letters*, volume 21, number 9, pages 501–503, September 2011.

Measurement Results





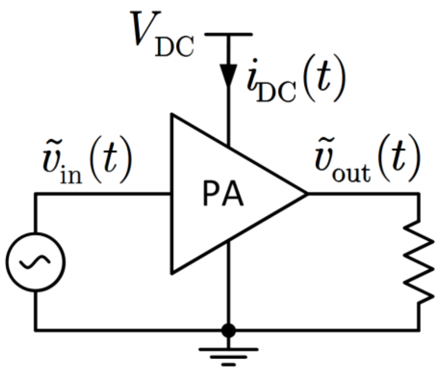
Performance at the competition

- ACPR -49.2 dB
- NMSE -35.7 dB
- Output power 24.4 dBm
- Drain efficiency 22.3 %

First place 71.8 points
Second place 68.9 points
Third place 63.2 points
(eight teams participating)

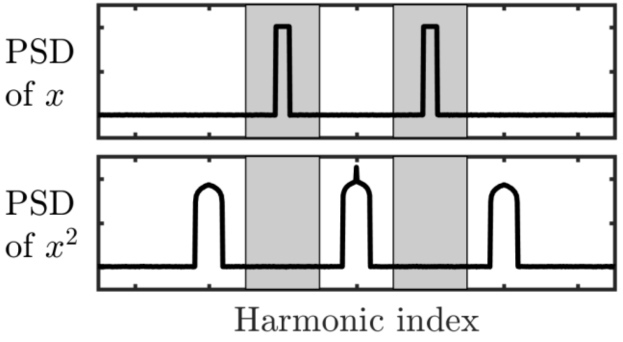
The presented methods were **successfully evaluated** against seven international competitors.

Thesis Summary



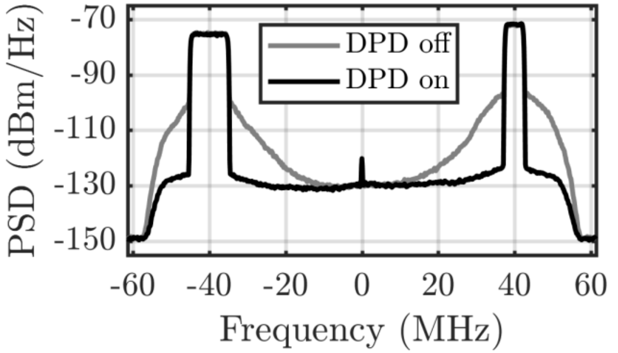
1. The linearity-efficiency trade-off

- Joint **linearity-efficiency model** of RF-PAs
- Linearity and efficiency quantification
- Architectures for highly efficient RF-PAs



2. Behavioral modeling of RF-PAs

- The first theoretical foundation for **even-order terms** in polynomial baseband models
- **Phase homogeneity** of complex baseband models of time-invariant passband systems



3. Digital predistortion of RF-PAs

- Dual-band **crest factor reduction**
- Dual-band vector-switched **digital predistortion**
- Training by **indirect** and **direct learning**

List of Publications

1. The Linearity-Efficiency Trade-off

[1] **H. Enzinger**, K. Freiberger and C. Vogel, "A joint linearity-efficiency model of radio frequency power amplifiers", *IEEE International Symposium on Circuits and Systems*, 2016.

2. Behavioral Modeling of RF-PAs

[2] **H. Enzinger**, K. Freiberger and C. Vogel, "Analysis of even-order terms in memoryless and quasi-memoryless polynomial baseband models", *IEEE International Symposium on Circuits and Systems*, 2015.

[3] **H. Enzinger**, K. Freiberger, G. Kubin and C. Vogel, "Baseband Volterra filters with even-order terms: Theoretical foundation and practical implications", *Asilomar Conference on Signals, Systems, and Computers*, 2016.

3. Digital Predistortion of RF-PAs

[4] **H. Enzinger**, K. Freiberger and C. Vogel, "Competitive linearity for envelope tracking: Dual-band crest factor reduction and 2D-vector-switched digital predistortion", *IEEE Microwave Magazine*, 2018.

[5] **H. Enzinger**, K. Freiberger, G. Kubin and C. Vogel, "A survey of delay and gain correction methods for the indirect learning of digital predistorters", *IEEE International Conference on Electronics, Circuits, and Systems*, 2016.

Related publications, not discussed within the thesis

[6] **H. Enzinger** and C. Vogel, "Analytical description of multilevel carrier-based PWM of arbitrary bounded input signals", *IEEE International Symposium on Circuits and Systems*, 2014.

[7] **H. Enzinger**, K. Freiberger, G. Kubin and C. Vogel, "Fast time-domain Volterra filtering", *Asilomar Conference on Signals, Systems, and Computers*, 2016.