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On the RF Transmitter Impairments in Beamforming

Nuutti Tervo

12.03.2024

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Contents

- RF Transmitter impairments
  - ➢ Focus: Nonlinear distortion of PAs
- A brief introduction to beamforming
- Nonlinear distortion in beamforming
- Array-level compensation mechanisms for RF impairments
- Conclusions

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RF Tx Impairments

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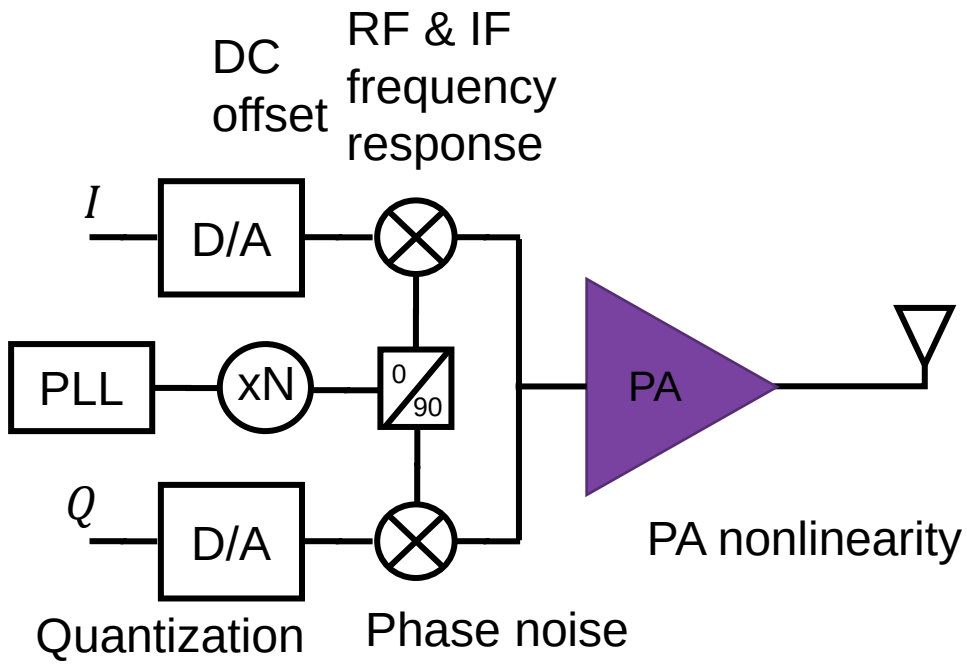
Tx impairments

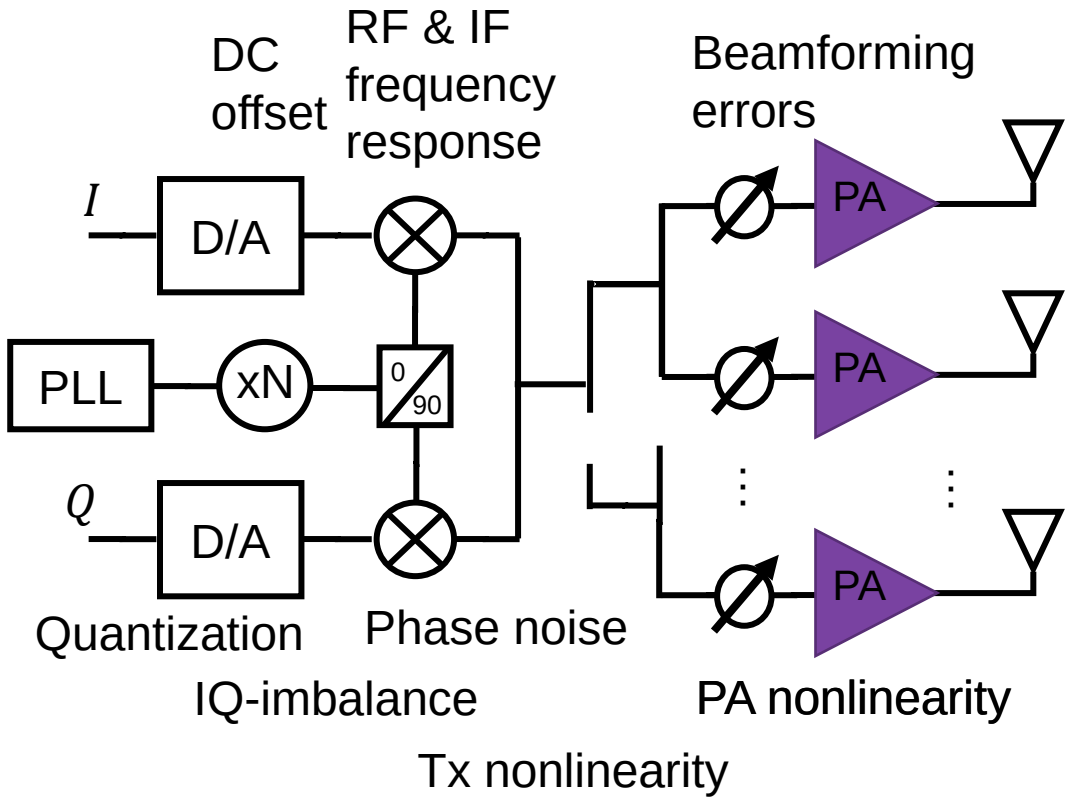


γ_Q γ_{IQ} γ_{PN} γ_{PA}

- Quantization noise & converter distortion
- IQ-imbalance
- DC offset
- Filter impairments
- Phase noise
- Thermal noise
- **PA nonlinear distortion**

[*] N. Tervo, M. E. Leinonen and A. Pärssinen, "On the Impact of RF Impairments in 6G Systems When Scaling Up the Frequency and Bandwidth", presentation in Workshop titled "International workshop on Wireless Communications in Terahertz (IWCT)" in 2023 EuCNC & 6G Summit, 6 June, Gothenburg, Sweden.

Tx impairments (array)



γ_Q γ_{IQ} γ_{PN} γ_{PA}

- Depending on the beamforming architecture, some impairments are *common* for antennas, but some may *differ* from antenna to antenna

[*] N. Tervo, M. E. Leinonen and A. Pärssinen, "On the Impact of RF Impairments in 6G Systems When Scaling Up the Frequency and Bandwidth", presentation in Workshop titled "International workshop on Wireless Communications in Terahertz (IWCT)" in 2023 EuCNC & 6G Summit, 6 June, Gothenburg, Sweden.

PA Nonlinear distortion in phased array

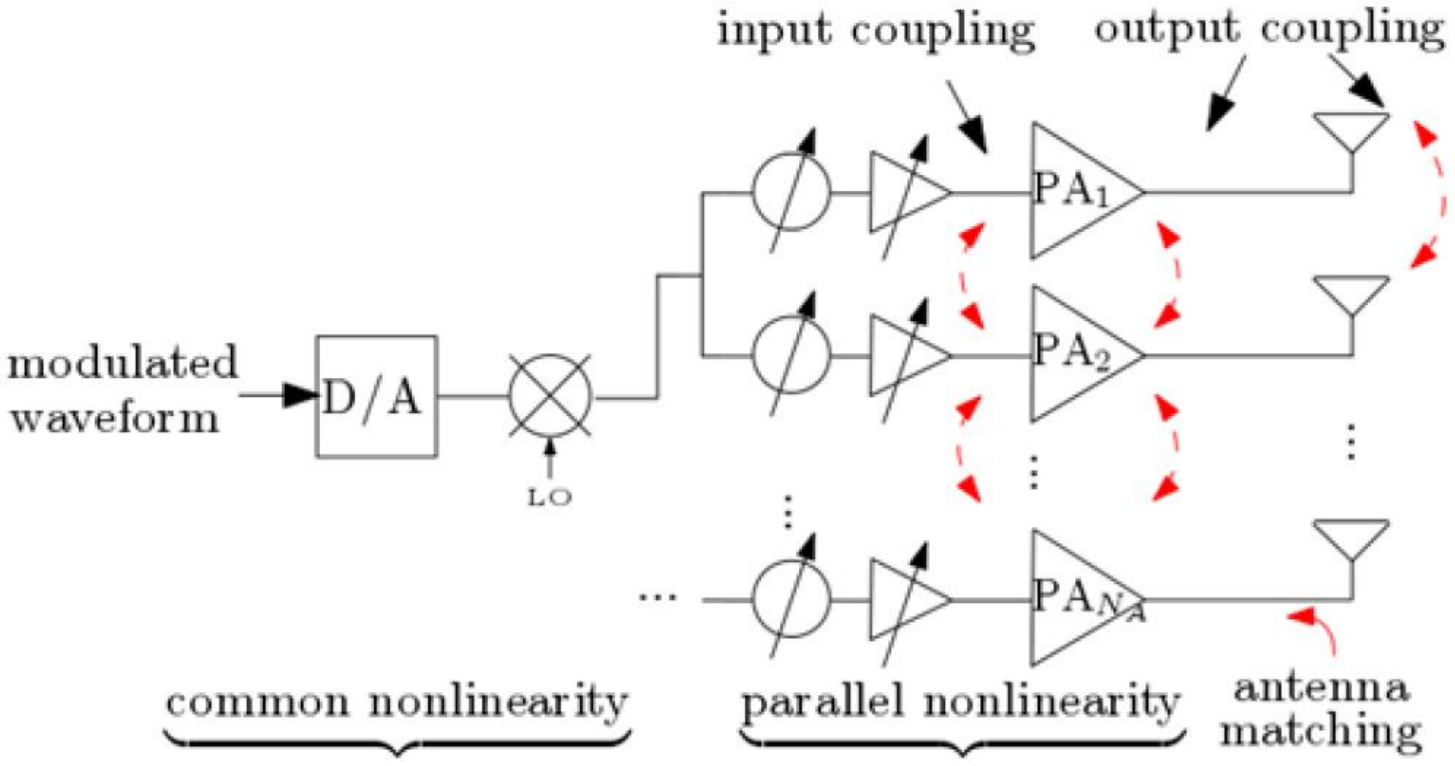


Fig. 1. Sources of nonlinearity in phased array transmitters.

- Common vs parallel sources of distortion
- PAs may have different nonlinear behavior due to
  - Beamforming
  - Process variations/manufacturing
  - Different loads (antennas)
  - Antenna/PA coupling
  - Thermal coupling
- How are the differences seen in the radiated signal?

[*] N. Tervo *et al.*, "Digital Predistortion Concepts for Linearization of mmW Phased Array Transmitters," *2019 16th International Symposium on Wireless Communication Systems (ISWCS)*, Oulu, Finland, 2019, pp. 325-329

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Beamforming

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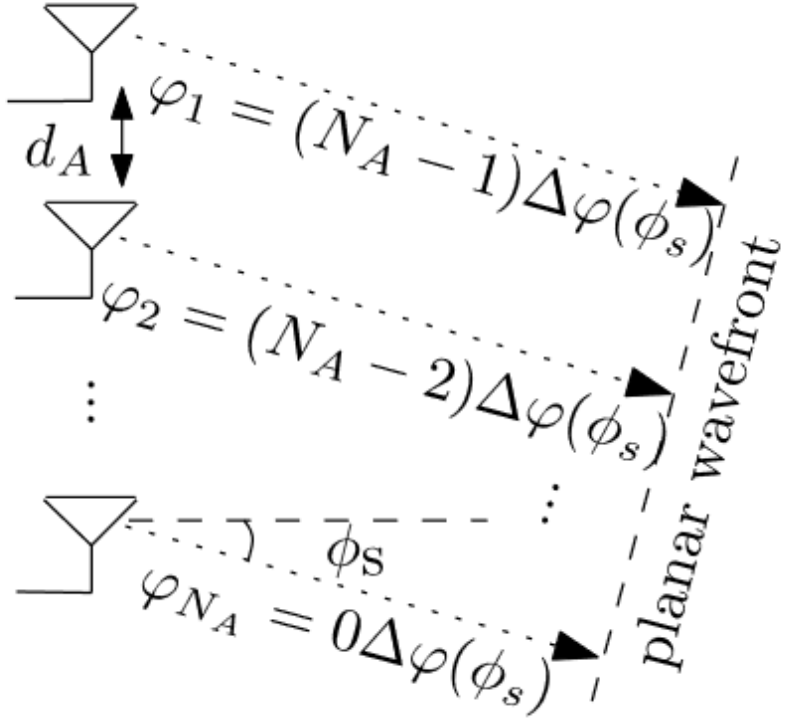
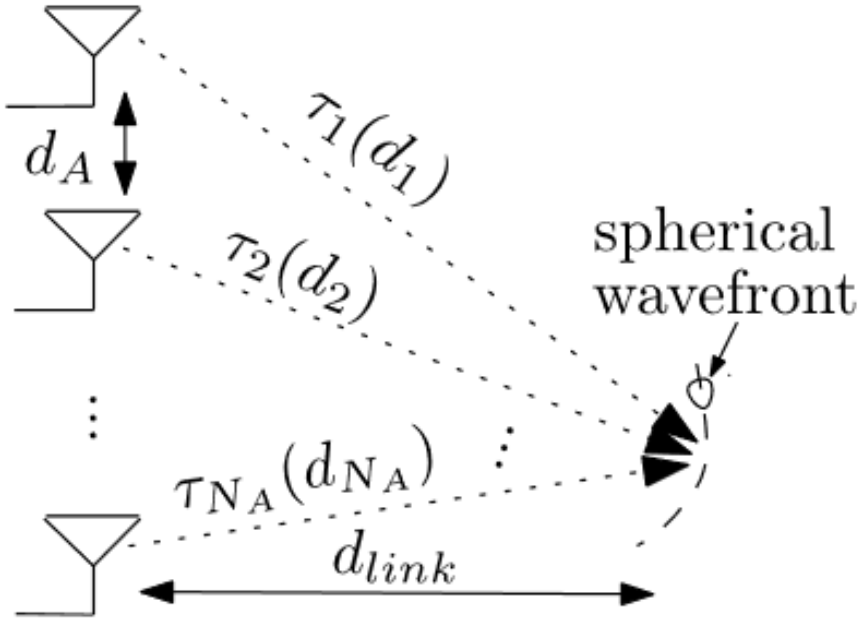
”Beamforming is combining signals over the air (to create maxima and minima)”

Beamforming is about combining signals!

- Beam steering: Signals meet at the same time and phase in the desired direction



Beam steering, narrowband

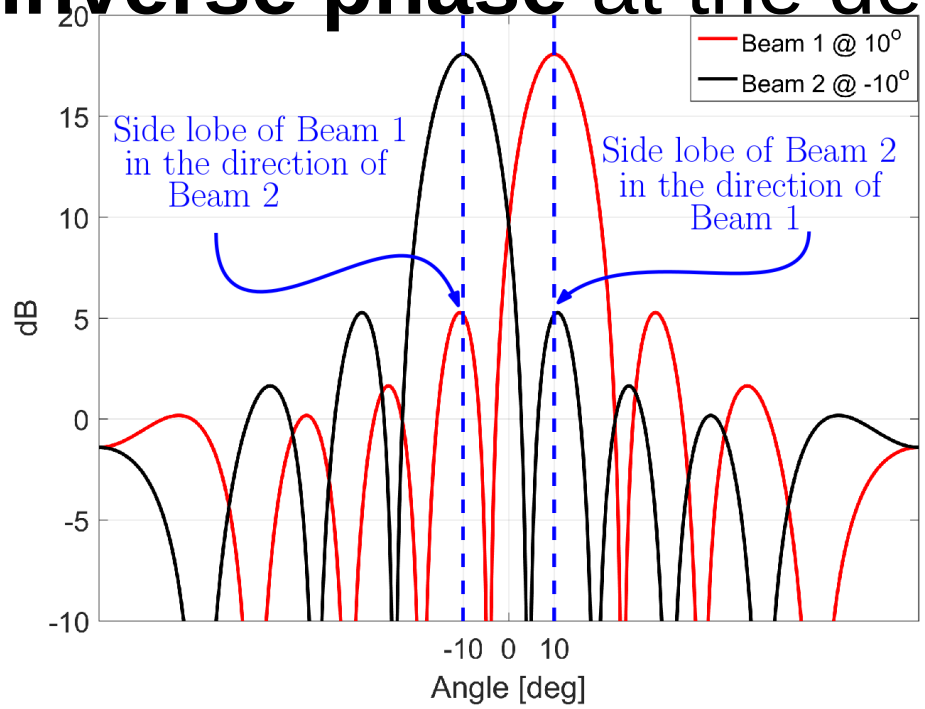


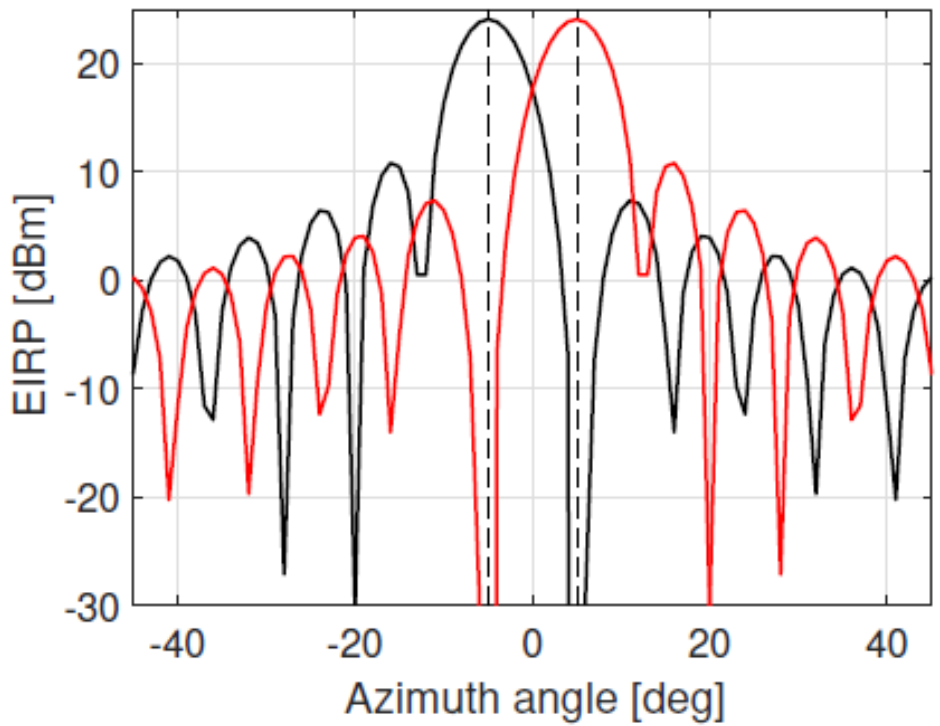
Beam focusing, wideband

N. Tervo, Doctoral Thesis, http://jultika.oulu.fi/Record/isbn978-952-62-3208-9

Beamforming is not only about directing power!

- Nulling/zero forcing: Signals meet at the same time but **inverse phase** at the destination





[*] M. Y. Javed et. al., "Inter-beam Interference Reduction in Hybrid mmW Beamforming Transceivers," *2018 IEEE 29th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Bologna, Italy, 2018, pp. 220-224, doi: 10.1109/PIMRC.2018.8580901.
[**] M. Y. Javed et. al., "Wideband Inter-Beam Interference Cancellation for mmW/Sub-THz Phased Arrays With Squint," in *IEEE Transactions on Vehicular Technology*, vol. 72, no. 6, pp. 7560-7572, June 2023, doi: 10.1109/TVT.2023.3242133.

”To control/vary the beam shape or direction, one must create differences between the signals in each antenna”

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Do RF Impairments Get Beamformed? Case Nonlinear Distortion

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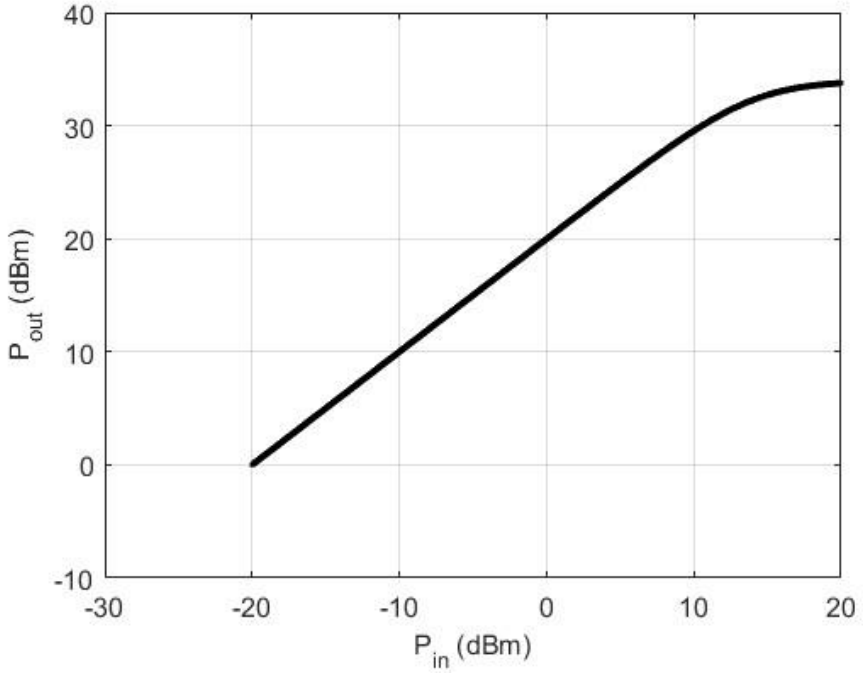
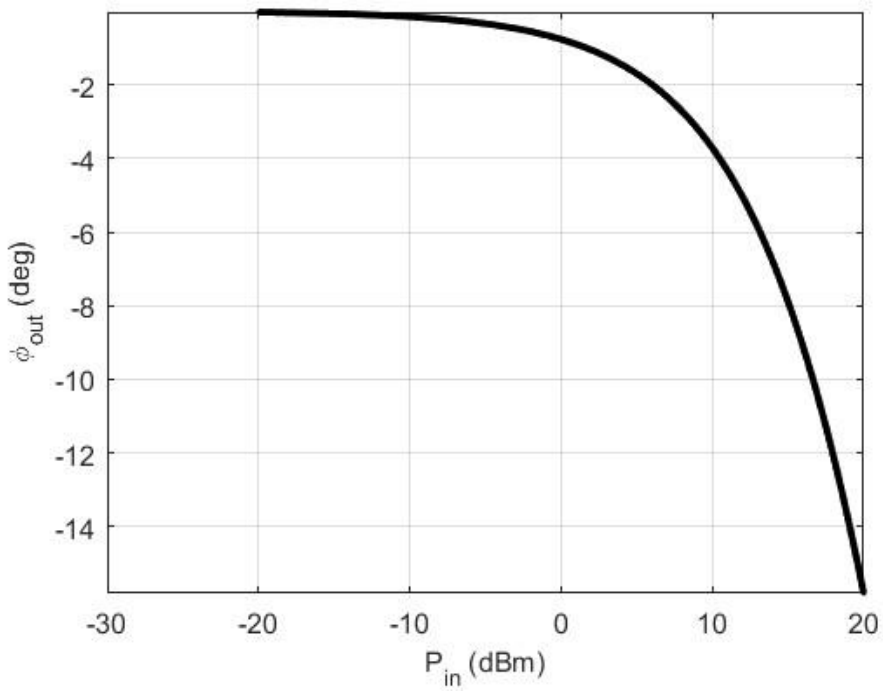
(oversimplified) Example: PA Nonlinear Distortion

- 4-element uniform linear array (ULA) with $\frac{\lambda}{2}$ antenna spacing
- PAs follow the modified Rapp model (AMAM/AMPM)

AMAM

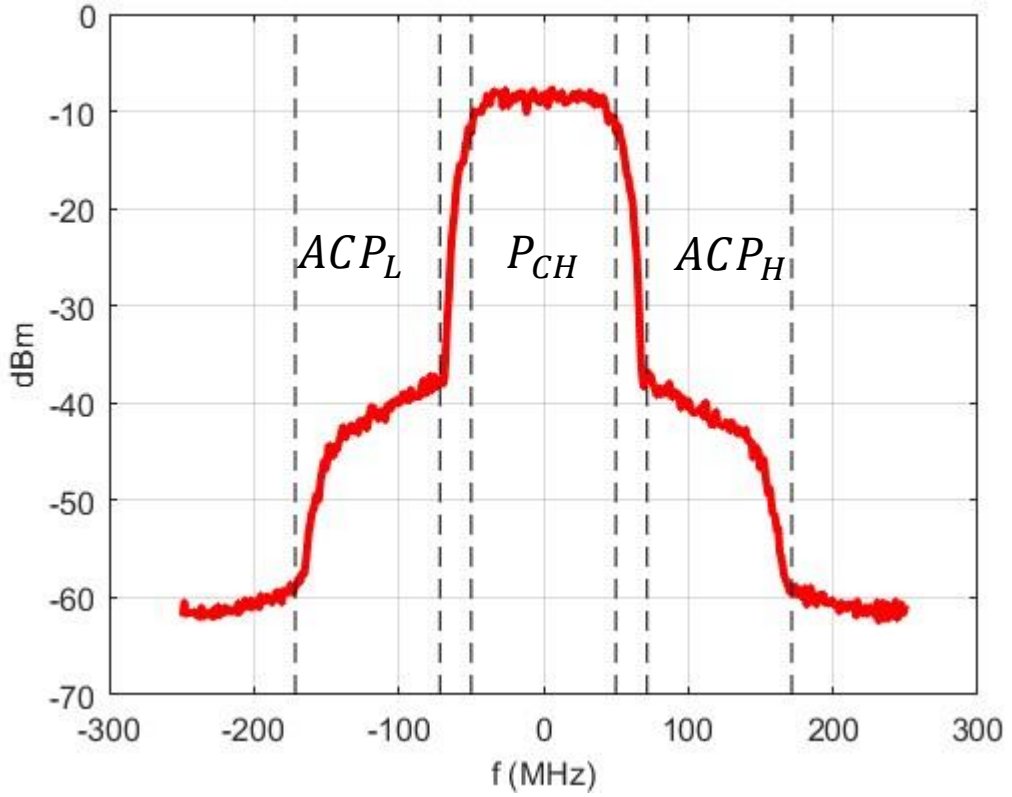


AMPM

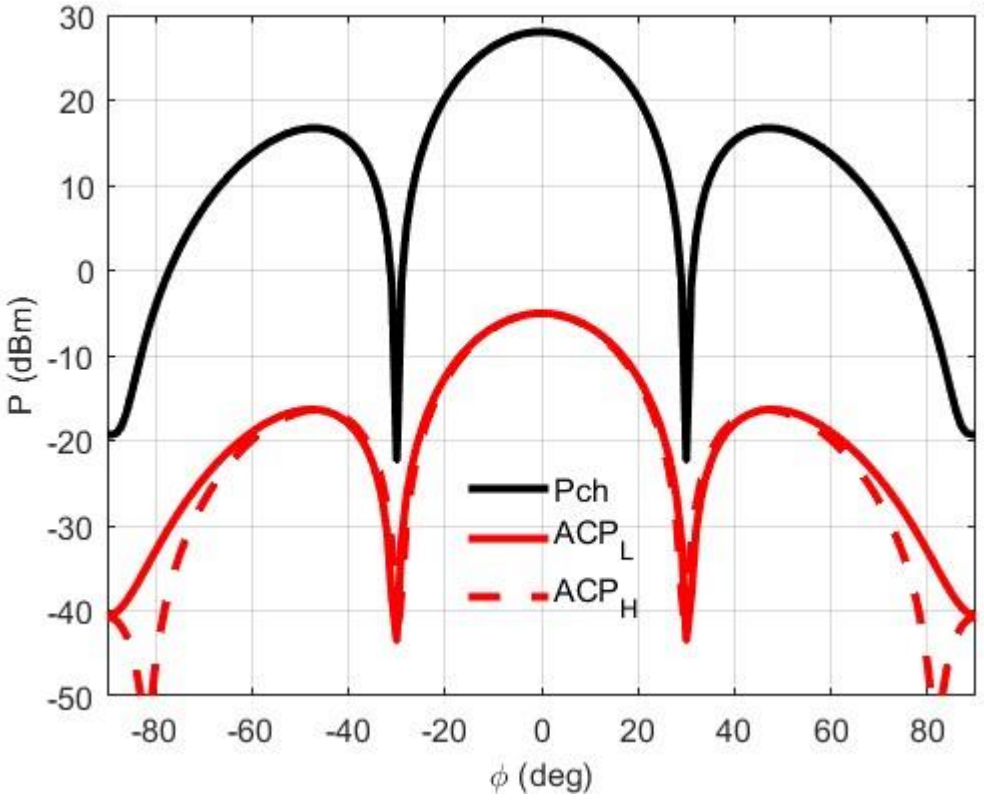


Case 1A: Nonlinear distortion, all PAs/signals similar*

Spectrum in boresight



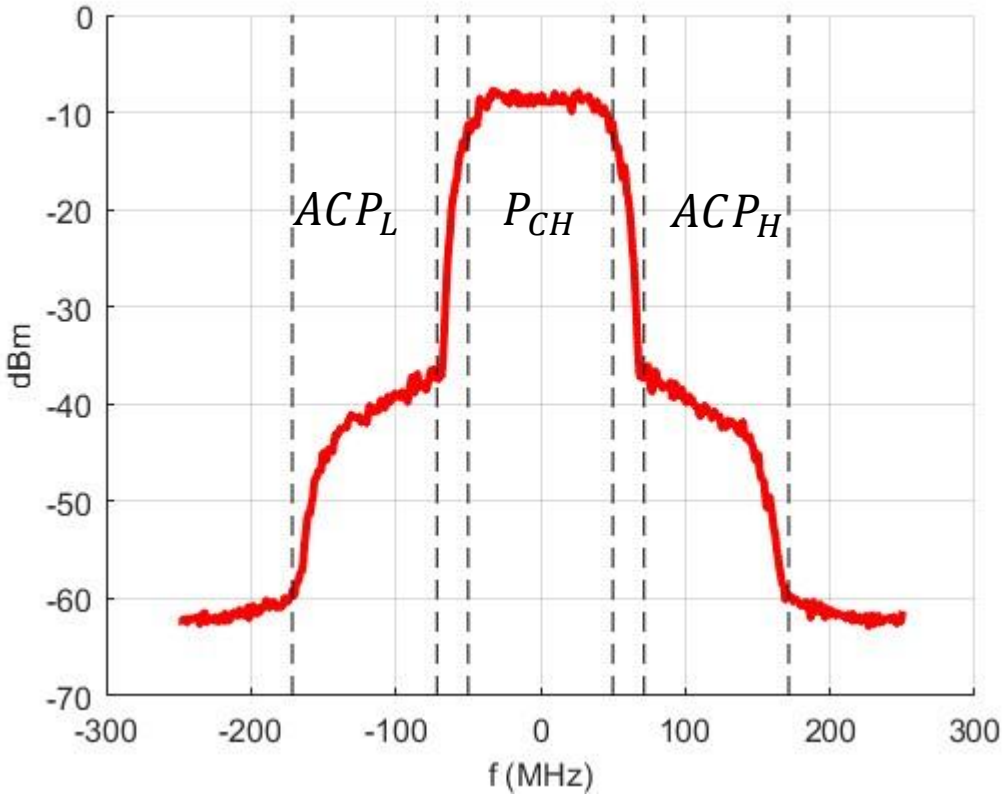
Beams of channel power and ACPs



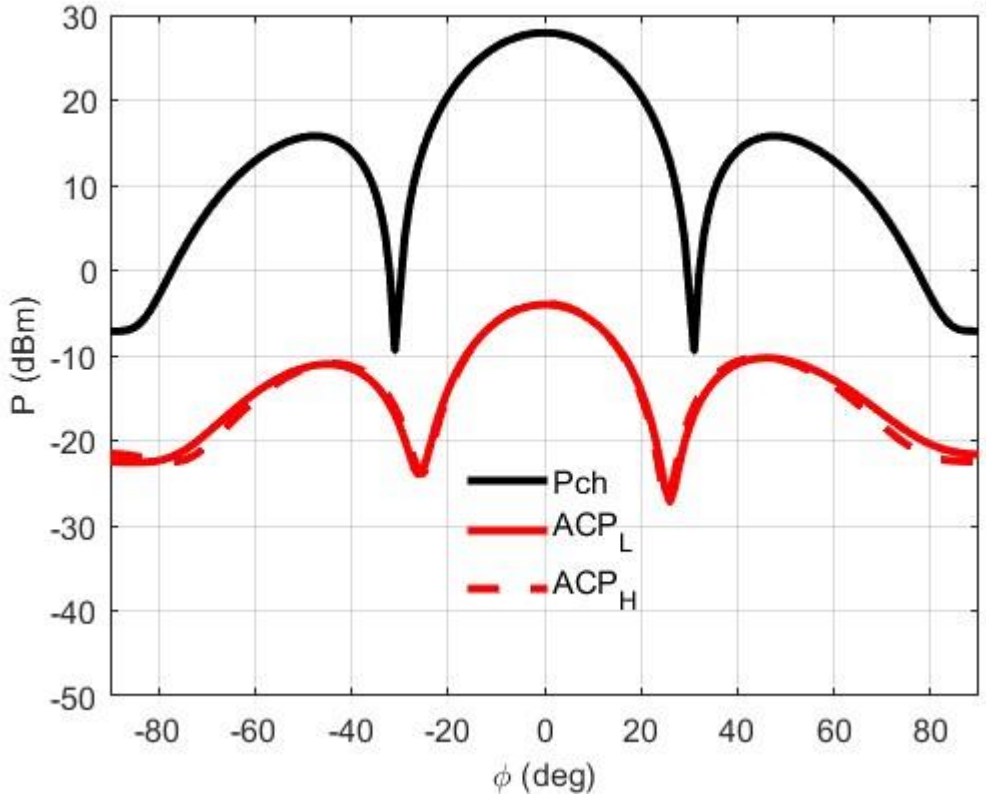
**Four PAs, all similar, uniform excitation, 256-QAM signal*

Case 1B: Nonlinear distortion, PAs different

Spectrum in boresight



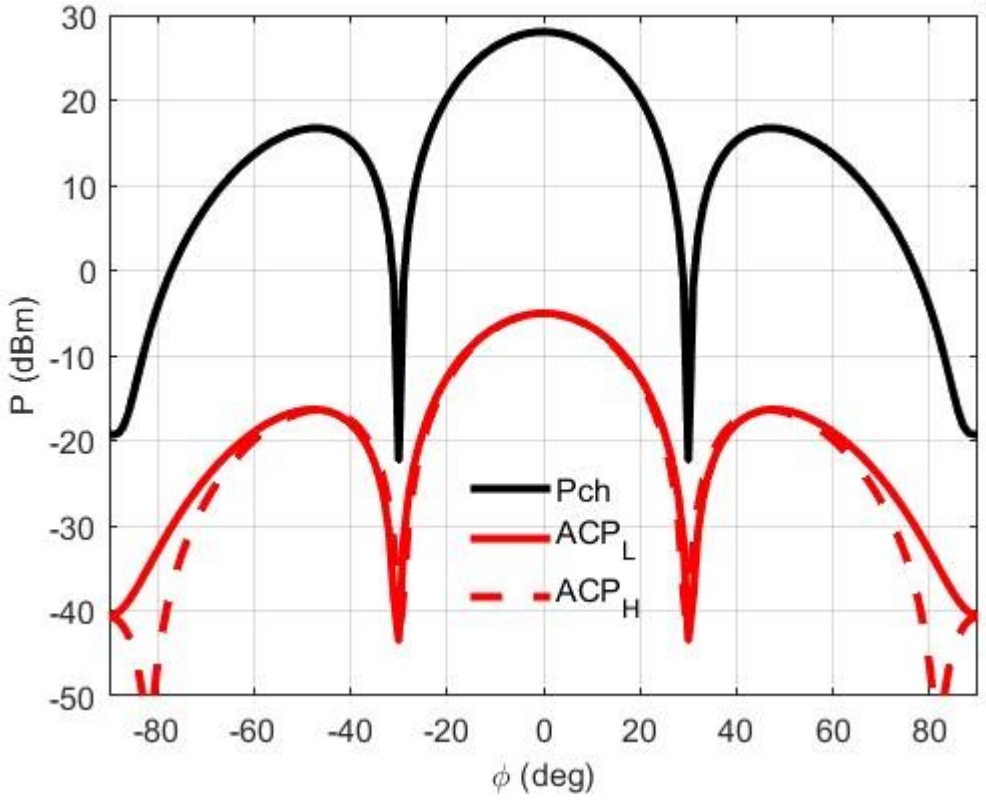
Beams of channel power and ACPs



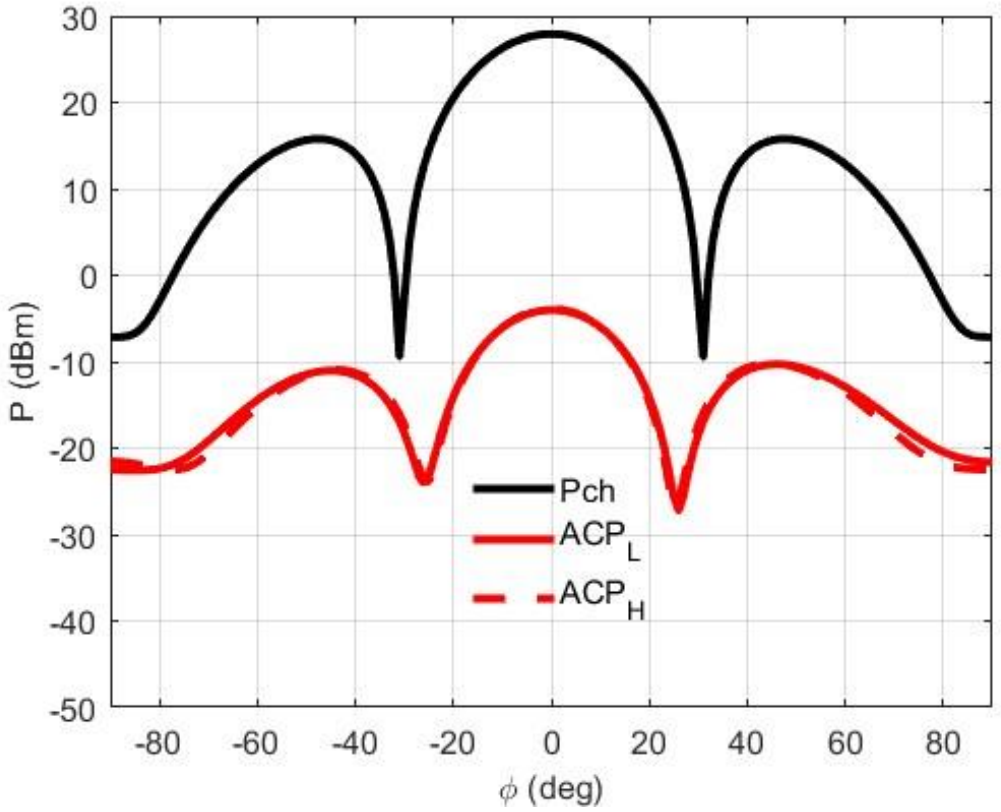
**Four PAs, all slightly different, uniform excitation, 256-QAM signal*

Cases 1A/B Comparison

Similar PAs



Different PAs



How differences are seen is a *different shape* in *beams of signal and distortion*!

*”If the **nonlinearities of individual transmit paths differ** from each other, the distortion **may have different beam shape compared with the beam of the linear part of the signal**”*

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Array-level mitigation of RF impairments: Case nonlinear distortion

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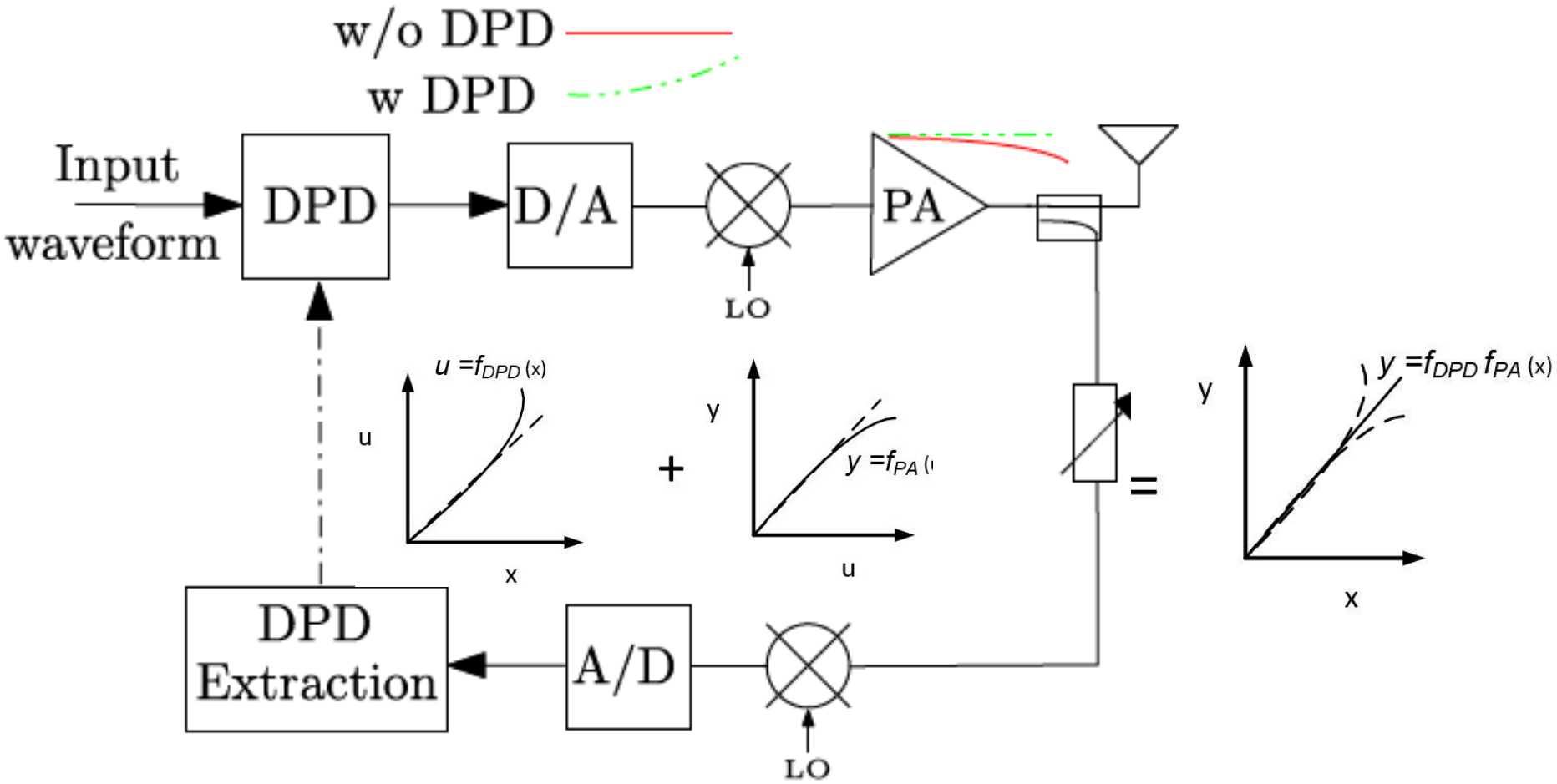
Linearization by digital predistortion (DPD)

Measure Output

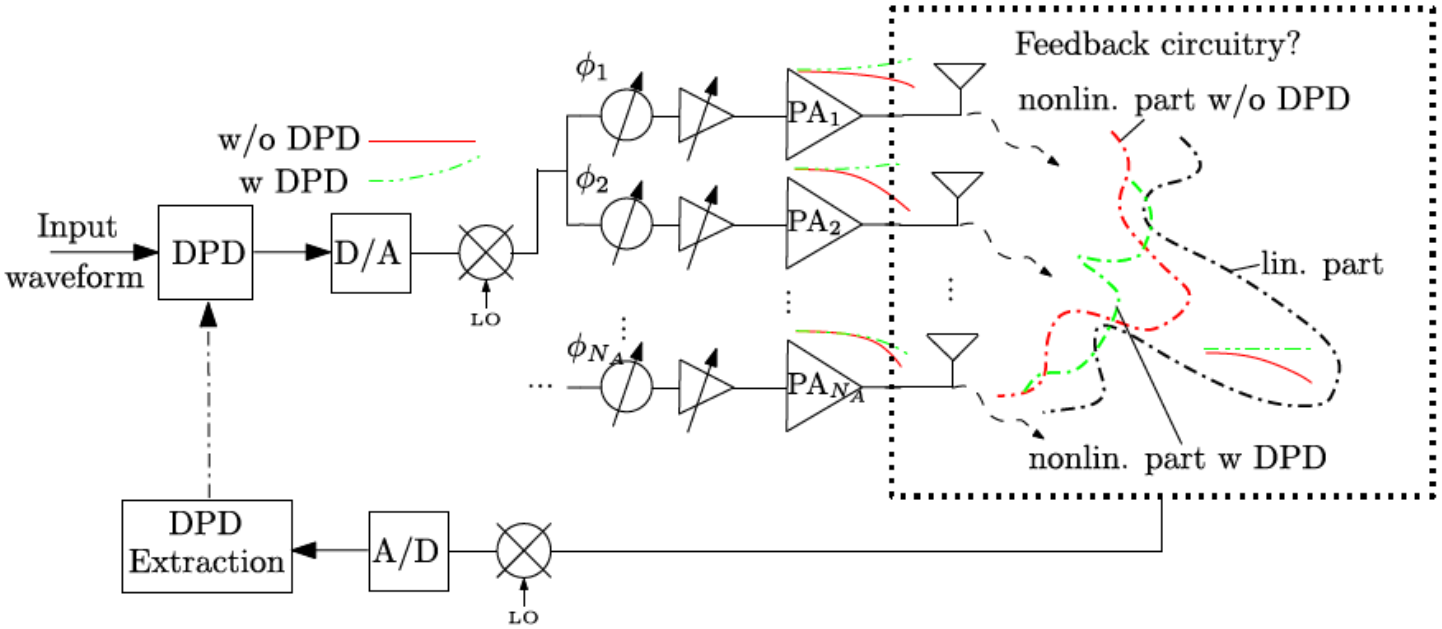
Model inverse of PA nonlinearity

Apply inverse at input to achieve linear output



N. Tervo, Doctoral Thesis, http://jultika.oulu.fi/Record/isbn978-952-62-3208-9

Array linearization by DPD



What if the PAs are **very** different?

- Impact of beamforming for the distortion
- Impact of DPD to the beam

N. Tervo, Doctoral Thesis,
http://jultika.oulu.fi/Record/isbn978-952-62-3208-9

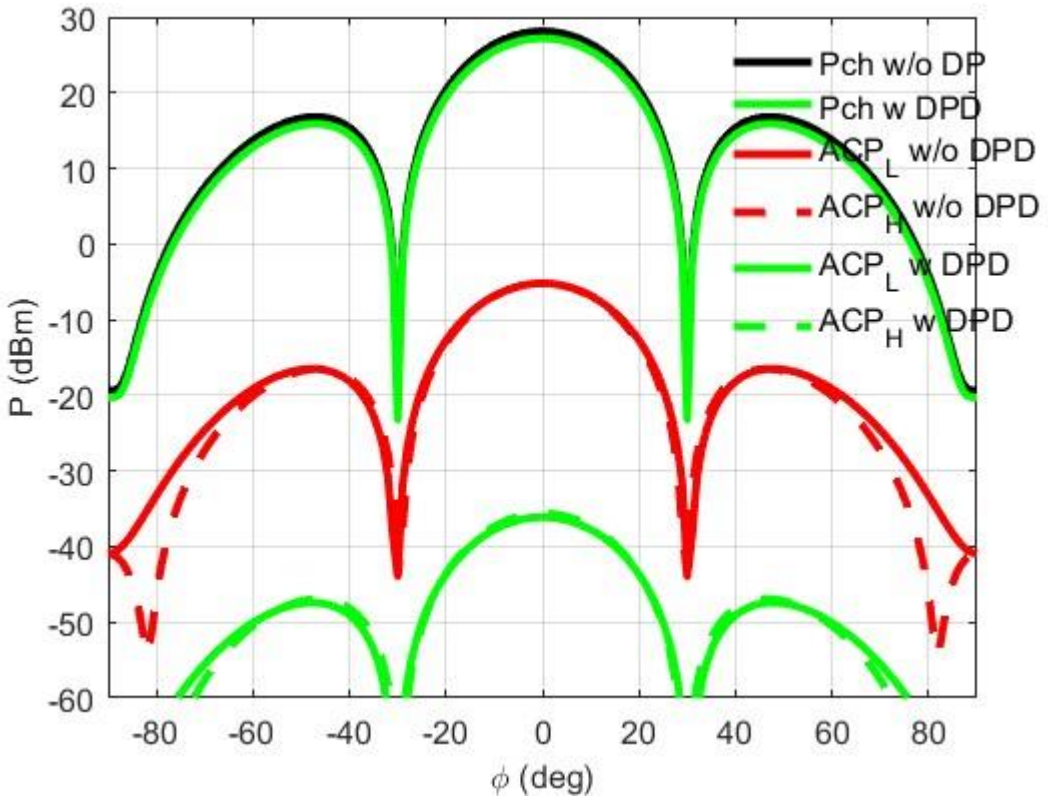
1. What to linearize?
   - What FOMs to improve?
   - Beam?

2. DPD is based on feedback measurements
   - How to arrange feedback in phased arrays for multiple paths?

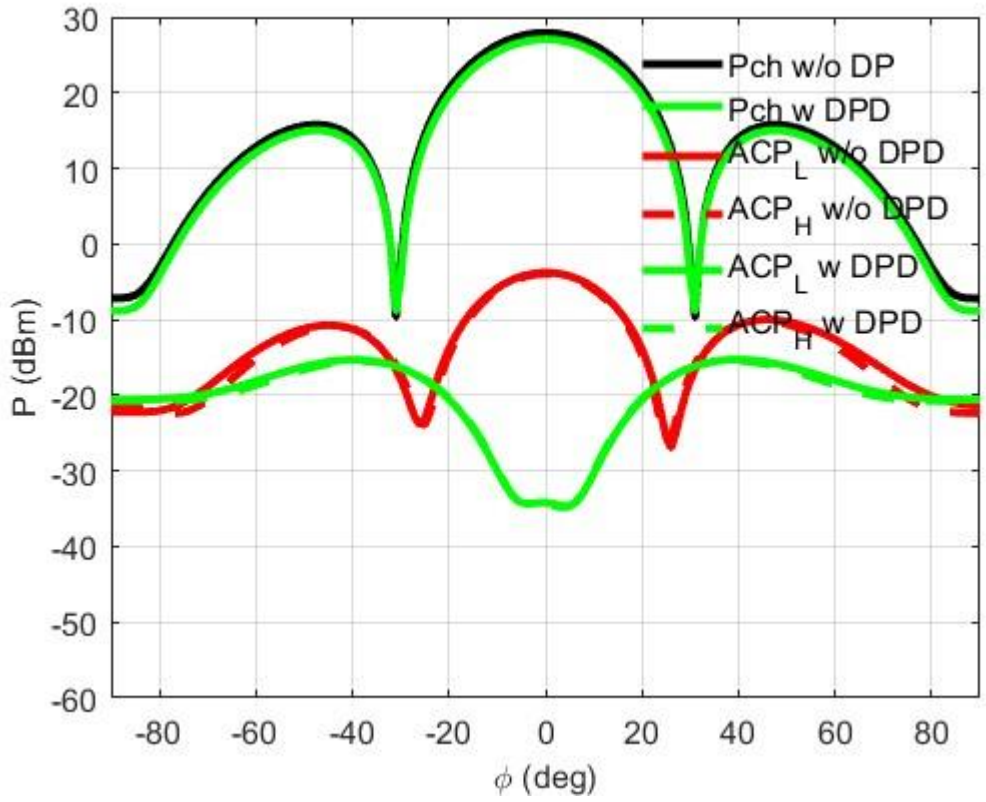
3. How to construct the DPD objective based on measurements?

Case 1C: DPD Linearization of cases 1A&B

Similar PAs



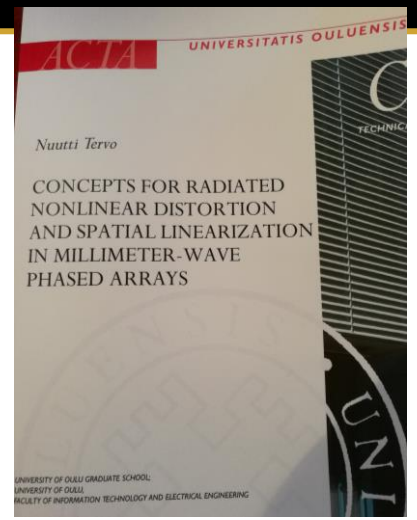
Different PAs

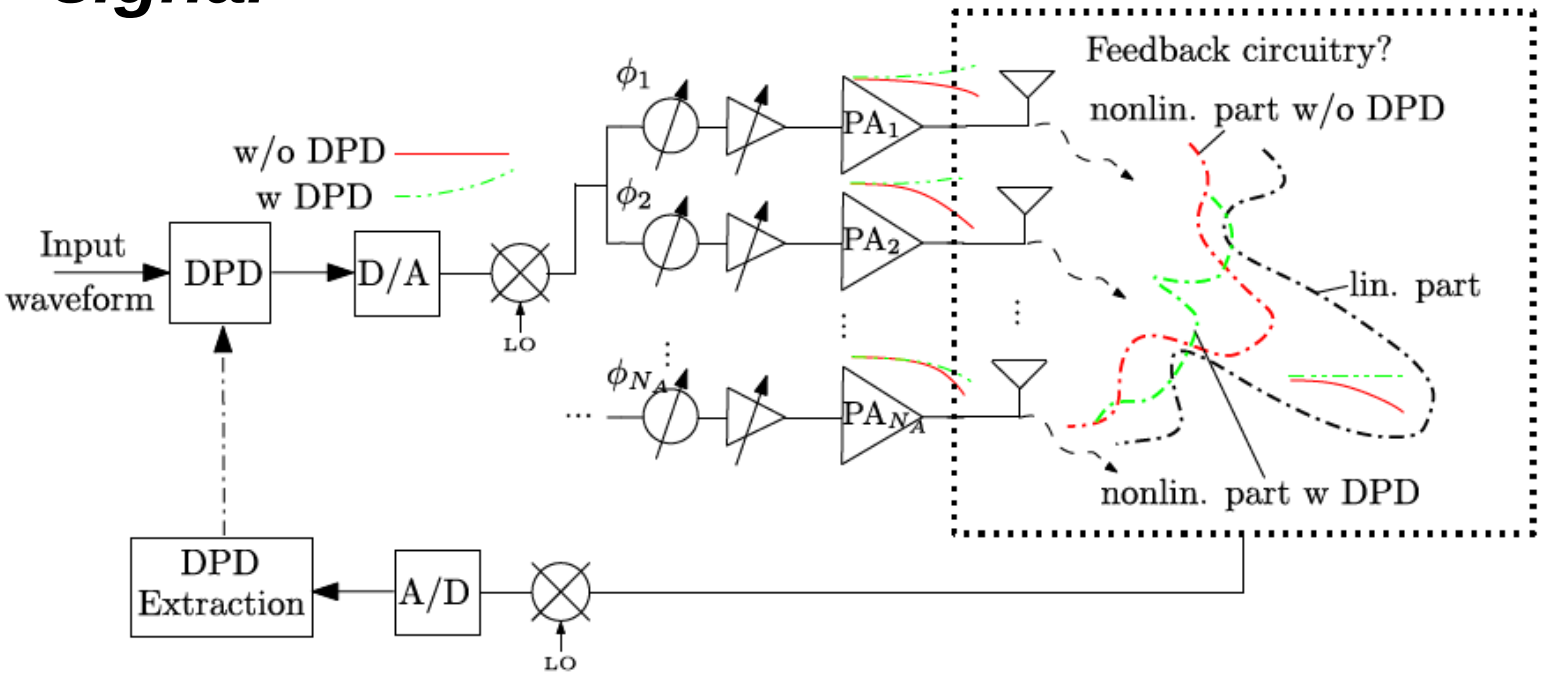


With array DPD, *small differences over PAs* create *major differences in the beam of the distortion*!

Concepts for Beamforming Nonlinear Distortion

*”If the **nonlinearities of individual transmit paths differ** from each other, the distortion **may have different beam shape compared with the beam of the linear part of the signal”***





This phenomenon is extremely important to understand in phased array linearization!

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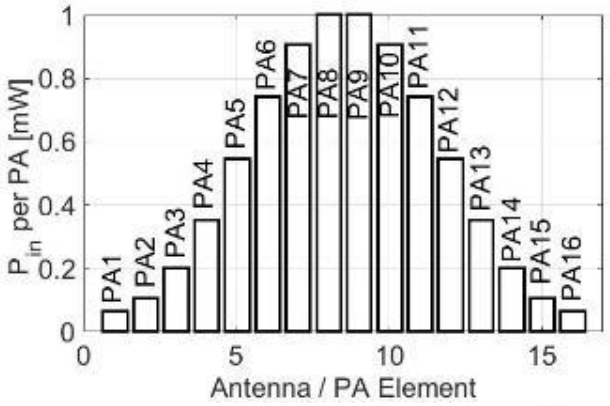
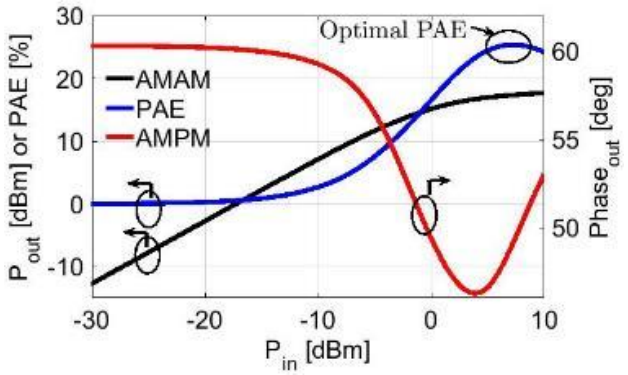
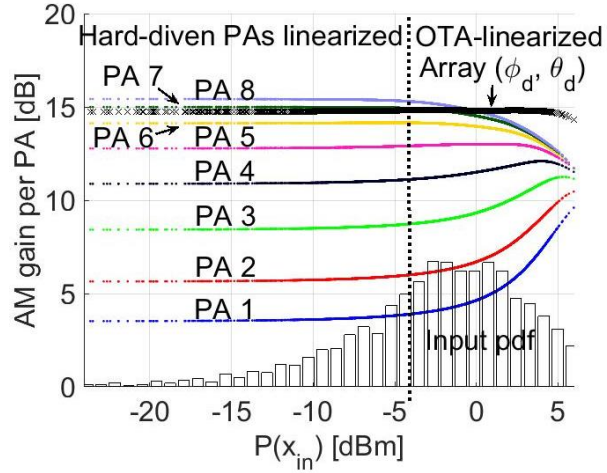
”Linearization by beamforming is about nulling/reducing distortion in a certain direction/position by combining multiple nonlinear components over the air”

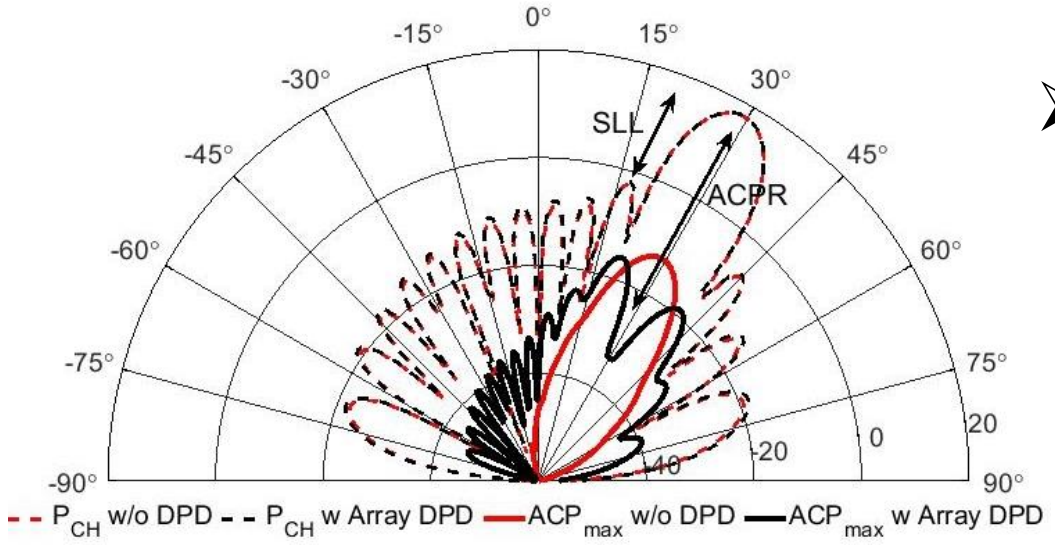
Case 2: DPD of Amplitude-Tapered Array

- DPD makes **PAs with low drive to expand**, which partly **compensates the compression of hard-driven PAs**!







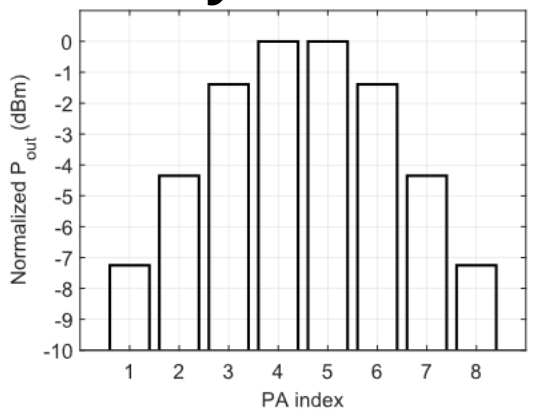


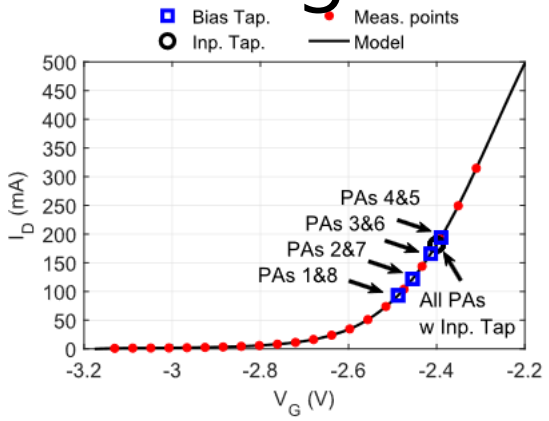
- DPD produce a "notch" in the steering angle

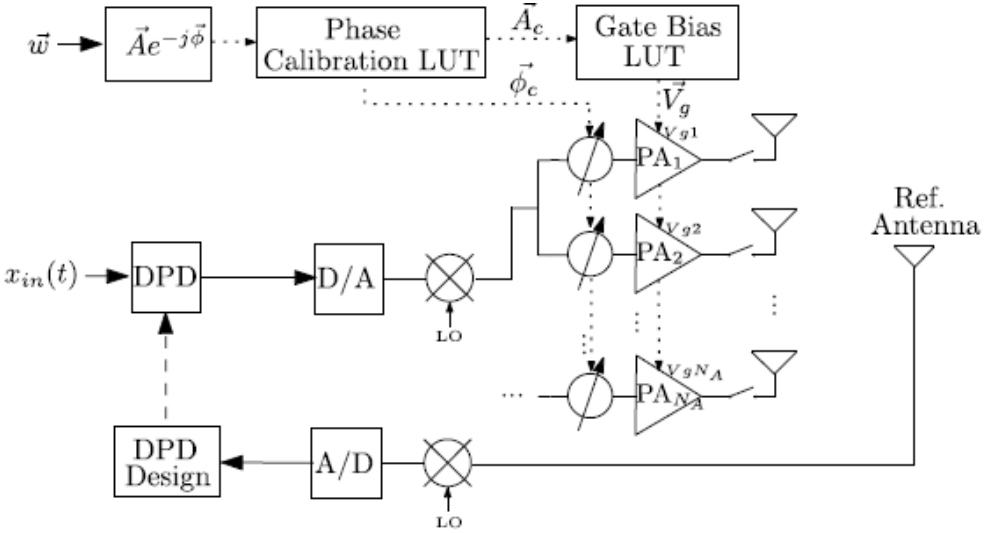
[*] N. Tervo, J. Aikio, T. Tuovinen, T. Rahkonen and A. Parssinen, "Digital predistortion of amplitude varying phased array utilising over-the-air combining," *2017 IEEE MTT-S International Microwave Symposium (IMS)*, Honolulu, HI, USA, 2017, pp. 1165-1168, doi: 10.1109/MWSYM.2017.8058809.

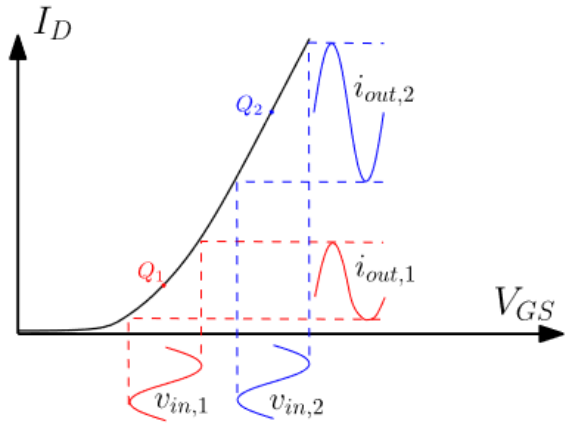
IF we want more ”omnidirectional” DPD performance, we need to make nonlinearity of individual paths similar

- One way to use PA biasing









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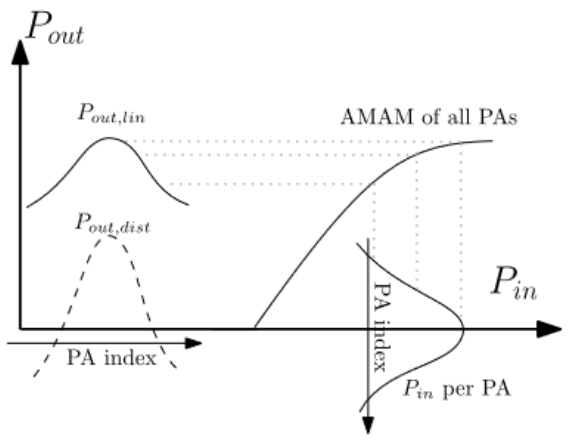
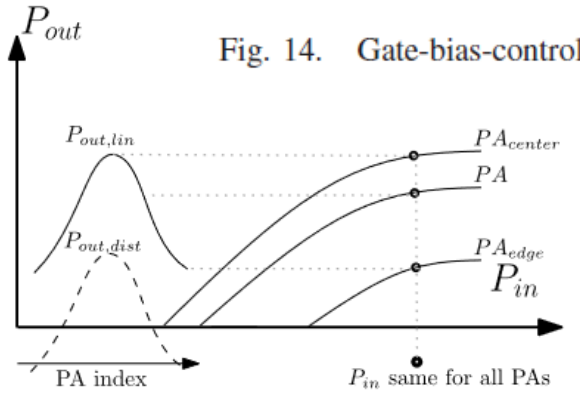


(b)

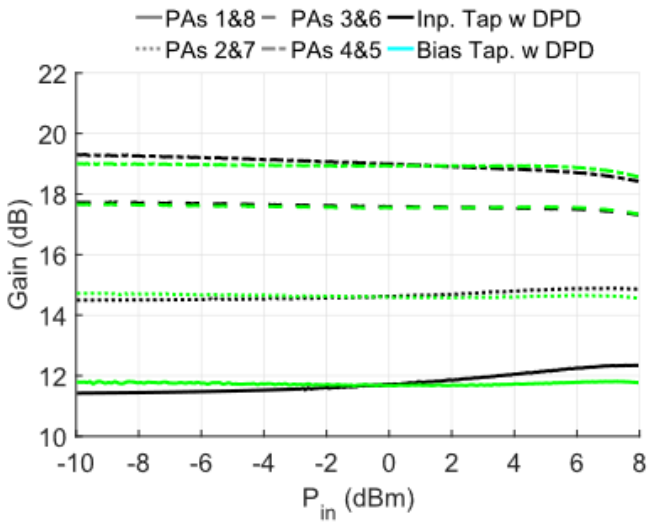


(c)

Fig. 14. Gate-bias-controlled beamforming and array DPD.

[*] N. Tervo *et al.*, "Combined Sidelobe Reduction and Omnidirectional Linearization of Phased Array by Using Tapered Power Amplifier Biasing and Digital Predistortion," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 69, no. 9, pp. 4284-4299, Sept. 2021, doi: 10.1109/TMTT.2021.3092357.

Fewer differences in PAs = more omnidirectional DPD perf



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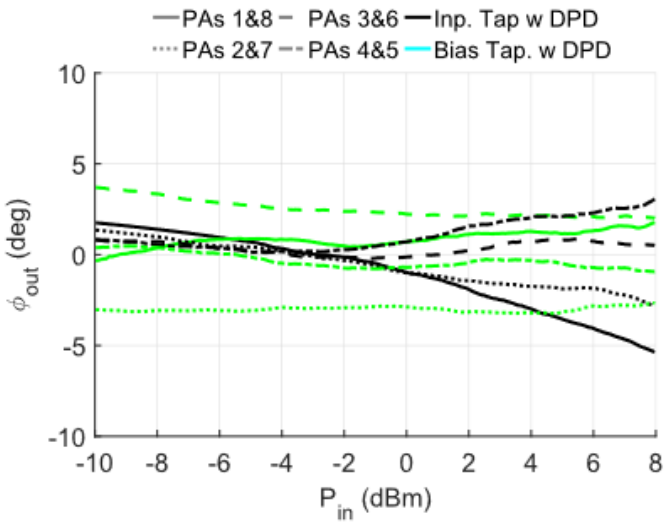

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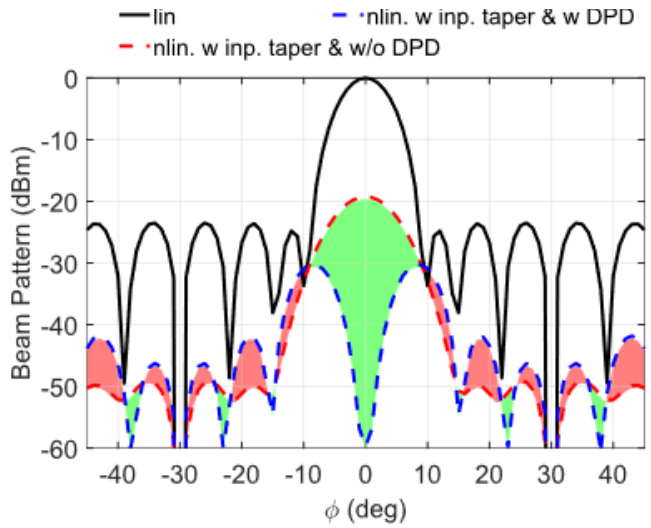

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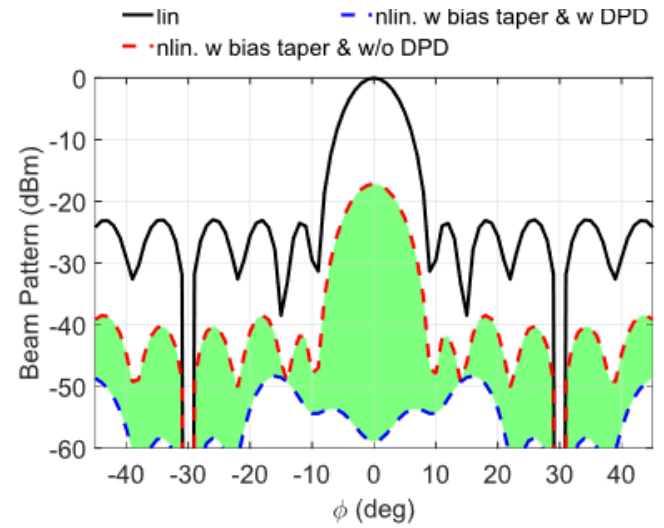
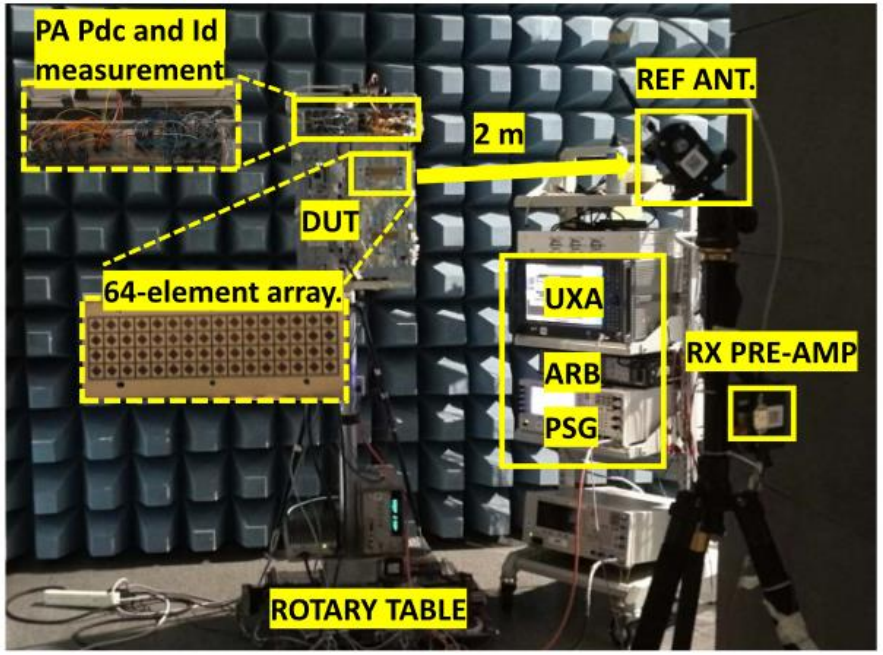


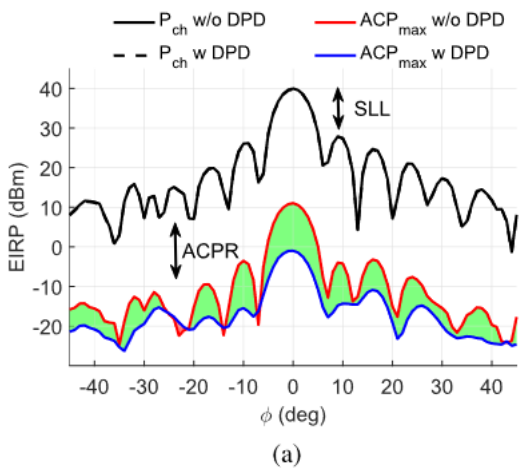
(b)

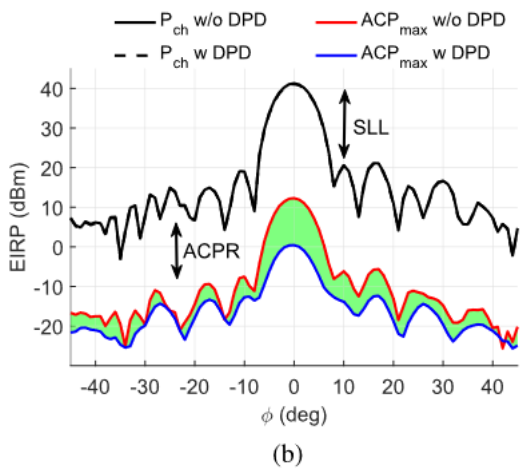
Experiments with 28 GHz phased array with GaN PAs

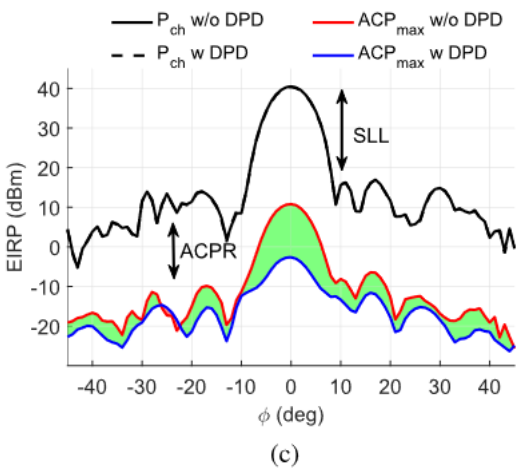


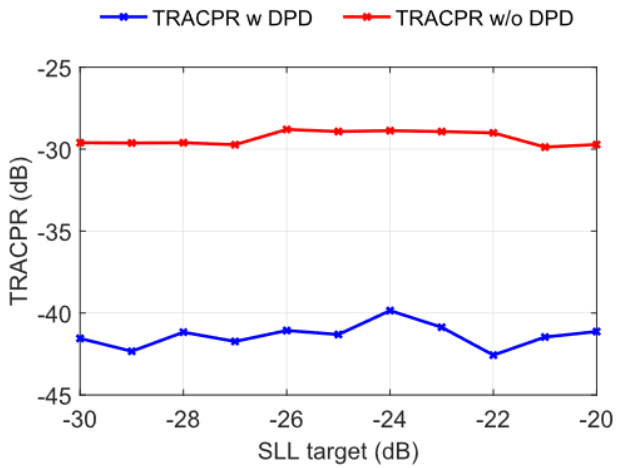
Per-antenna amplitude control done using PA biasing

- Achieve better efficiency and make the nonlinearity of the paths similar
- Cause: Radiated DPD performance can be made more omnidirectional

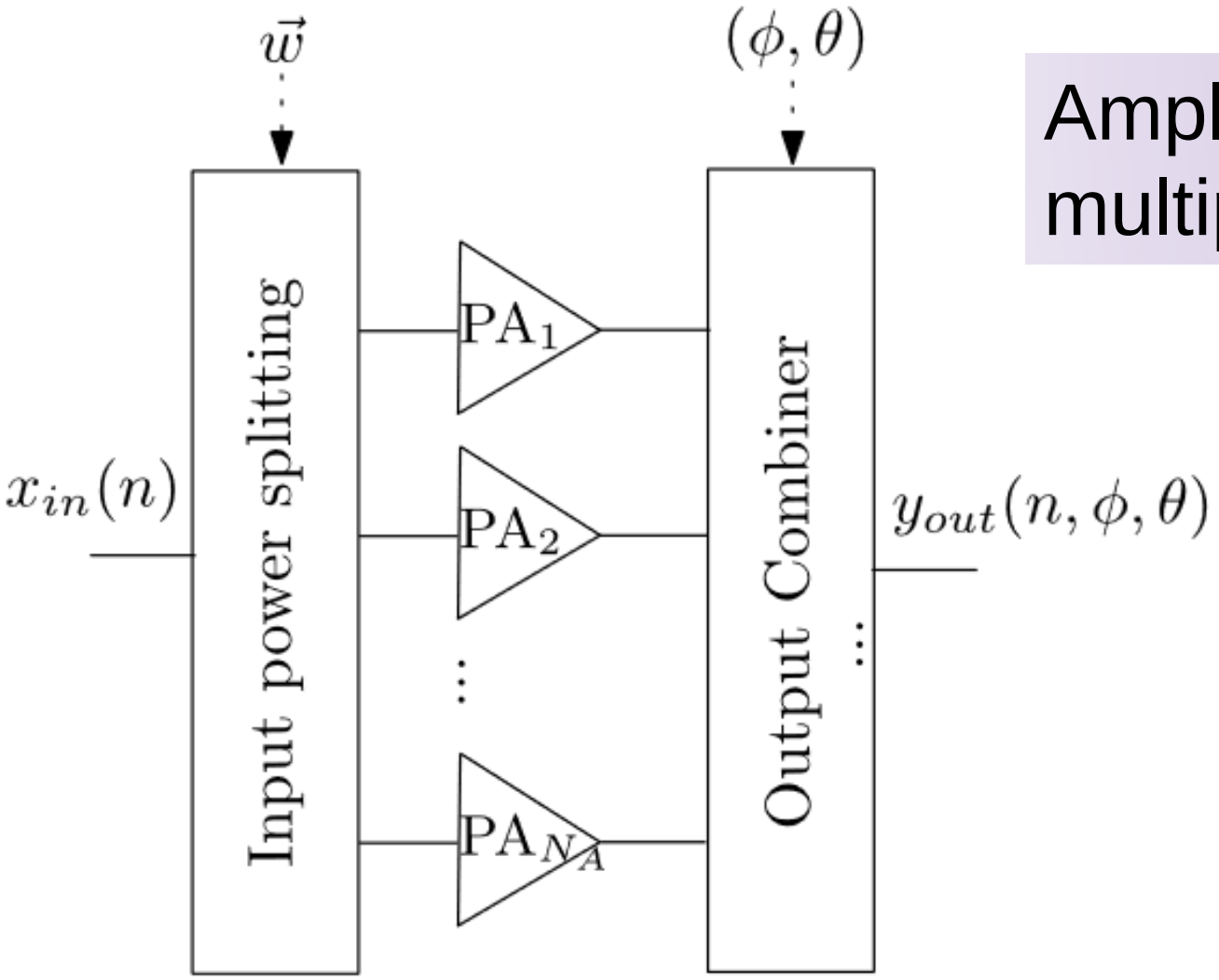








Beamforming from PA perspective?



Amplification ”just” divided into multiple antenna paths☺

Many linearization techniques can be also used in array-level

- LINC/outphasing
- feed-forward
- predistortion
- …

N. Tervo, Doctoral Thesis, http://jultika.oulu.fi/Record/isbn978-952-62-3208-9

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What about other RF impairments?

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Can Spatial Combining Help to Reduce and Compensate also other RF impairments?

Phenomenon	Impact for signal	How beamforming/OTA combining can help?
Quantization noise, nonlinearity	Decrease quality, spectral regrowth	Array-level summation of multiple converters, averaging (with dithering*), …
Thermal noise	Decrease quality	Array-level summation & averaging
Rx nonlinearity	Decrease quality, blockage	Array level AGC, spatial filtering of IMDs & blocking signal
Tx nonlinear distortion	Decrease quality, spectral regrowth	Array-level DPD/linearization concepts, averaging, spatial filtering of distortion, …
Phase noise	Decrease quality, random phase fluctuations, frequency error	Combining multiple mixers/LOs over the air, array-level phase noise compensation, …

*Dithering = use noise to randomize quantization noise between multiple paths and sum to get an averaging gain in SNDR

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The same in a couple of bullet points☺

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Conclusions

- Beamforming is about summing☺
  - "*Beamforming RF Impairments*" is about combining them over the air☺
- If impairment and (desired) signal have *differences* concerning each other from *antenna to antenna*, the impairment can also have a *different beam shape* than the linear signal
- Arrays offer possibilities for using spatial combining for the reduction and compensation of RF impairments
  - Many compensation techniques that are based on summing can be brought on antenna array-level!

Thank you!

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