

TH2F-5

Fast Simultaneous Distortion Measurement Technique for Mismatch Compensation of Doherty Phased-Array Beamformers

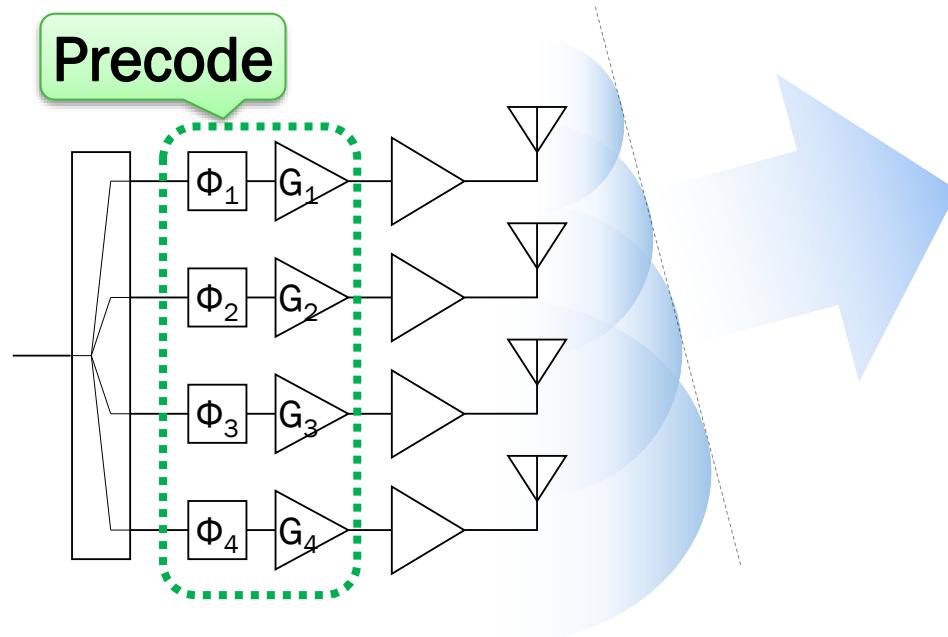
Yuuichi Aoki, Yonghoon Kim, Yongan Hwang, and Sung-Gi Yang
Samsung Electronics, Suwon, Korea



Outline

- Introduction / Motivation
- Algorithms
 - Phased-Array Gain/Phase Characterization with Orthogonal Code
 - Phased-Array IMD₃ Characterization with Orthogonal Code
- Calibration and Measurement
 - Fast Simultaneous IMD3 Measurement
 - Inter Element Mismatch Compensation
- Summary

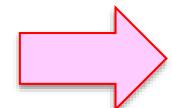
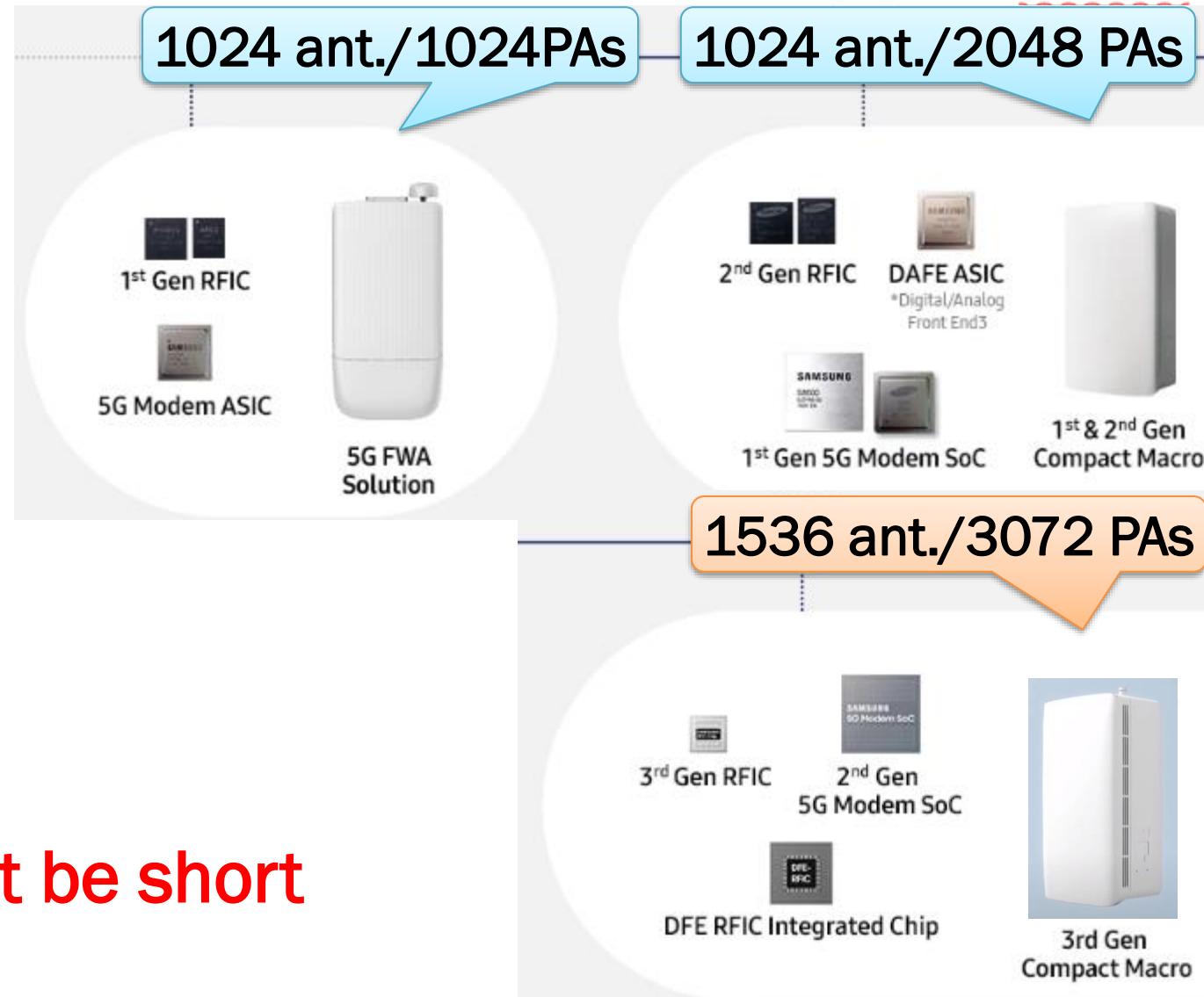
Phased Array Beamformer



- Create directional beams focusing onto user devices
- Beam direction steered in real time by precoding phases electrically
- Generally, calibration is needed to align inter-element mismatch (IEM)

3rd generation BS

- > 1500 antennas
- > 3000 PAs



Calibration time/PA must be short

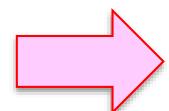
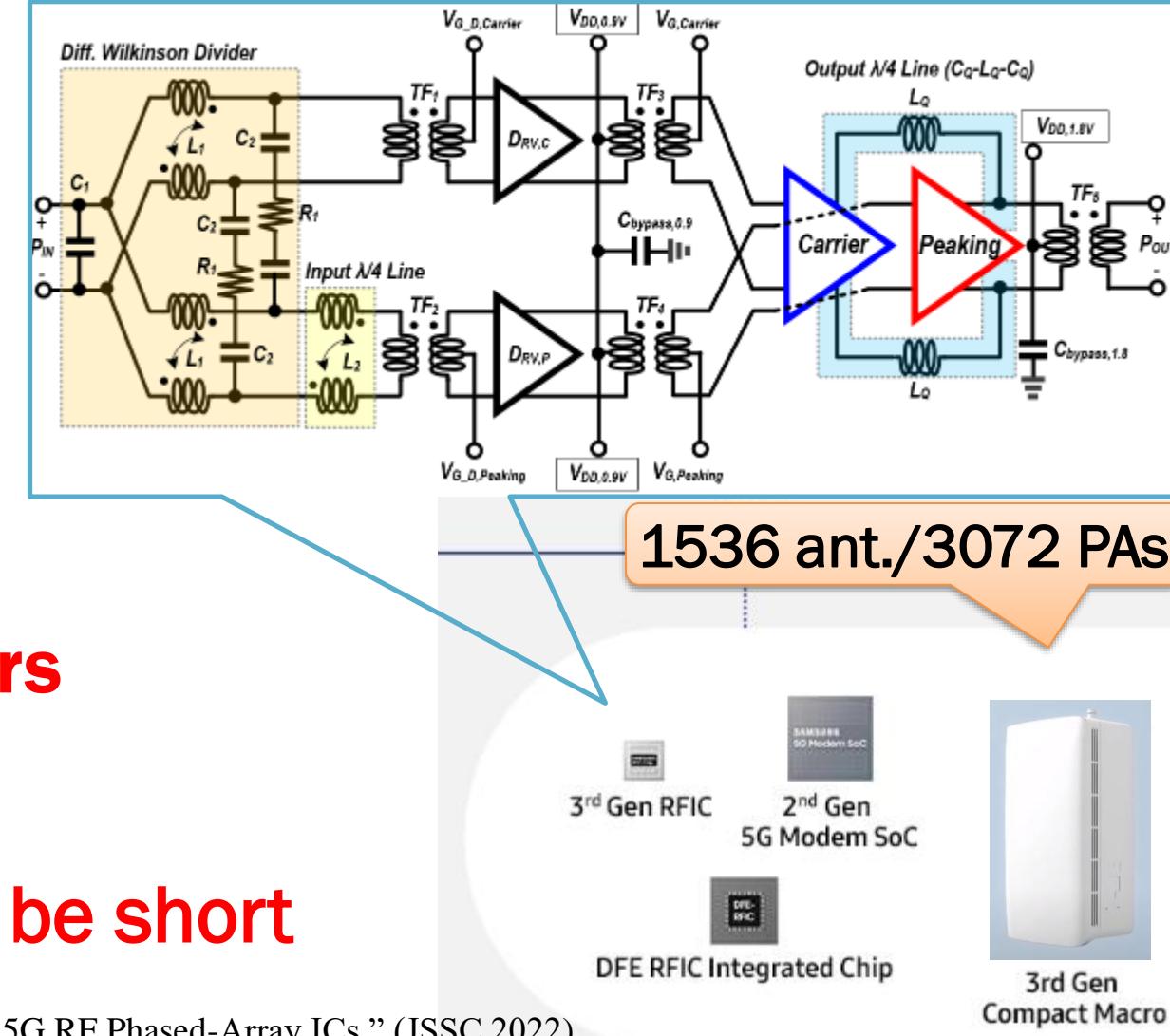
<https://www.samsung.com/global/business/networks/solutions/chipsets/>

<https://youtu.be/PON-kl2AYh8>

Doherty Power Amplifier

3rd generation BS

- > 1500 antennas
- > 3000 PAs
- Doherty PA (DPA) combining 2-differently biased amplifiers
- **> 6000 output-stage amplifiers**

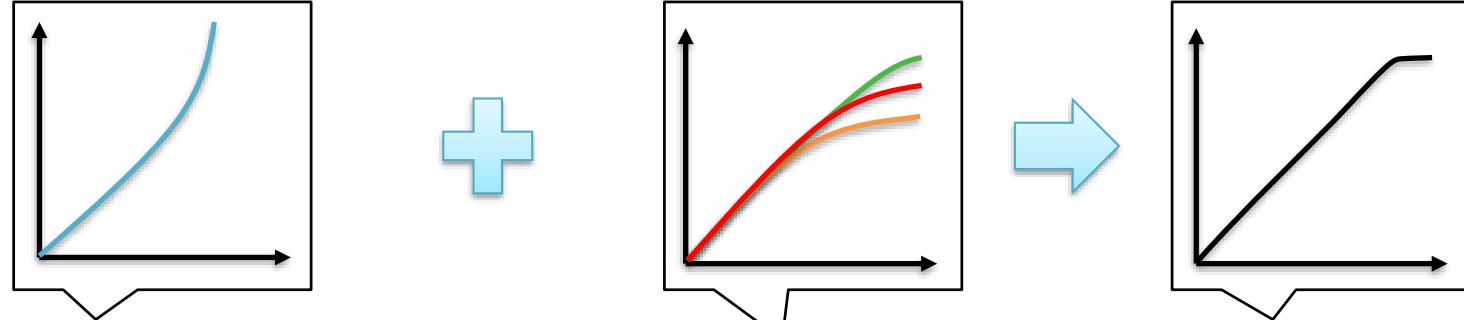


Calibration time/amp. must be short

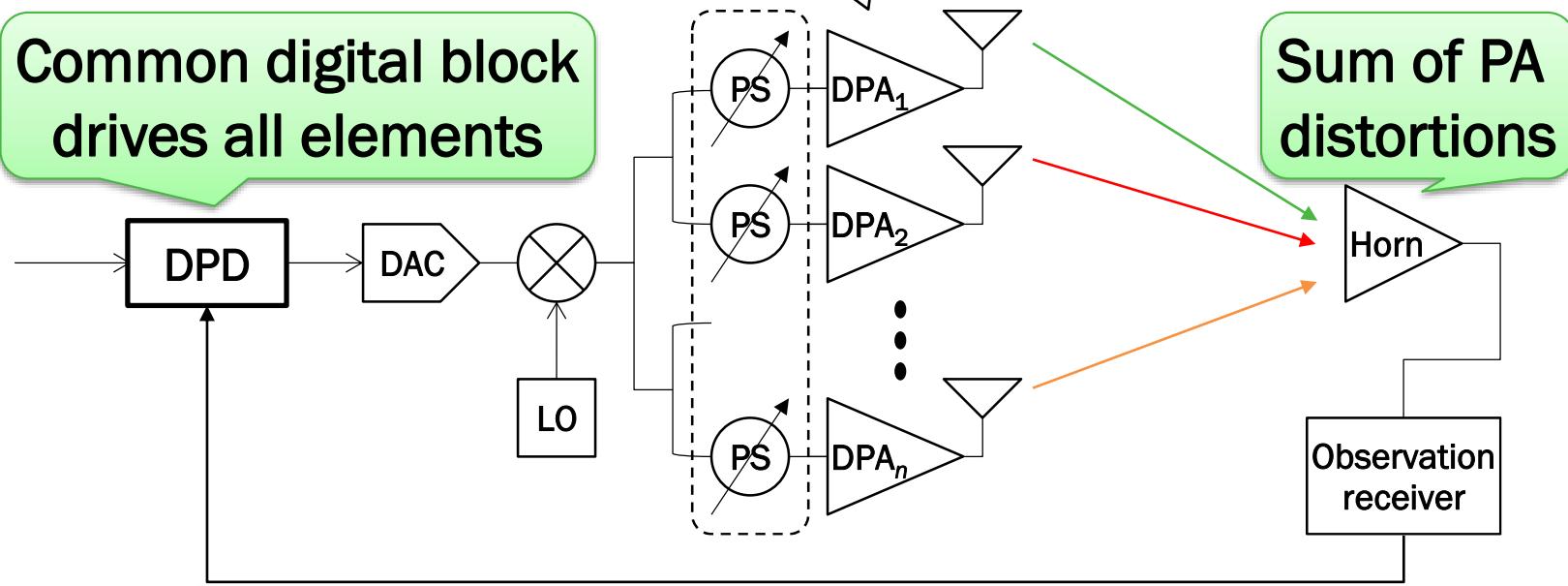
H. -C. Park *et al.*, "Single Transformer-Based Compact Doherty Power Amplifiers for 5G RF Phased-Array ICs," (JSSC 2022)

RTu2C-2: Joonho Jung *et al.*, "A 39 GHz 2 × 16-Channel Phased-Array Transceiver IC With Compact, High-Efficiency Doherty Power Amplifiers," (RFIC 2023)

DPD and Inter-Element Mismatch (IEM)



Common digital block drives all elements



Extract distortion
from common feedback

Actual distortion of each PA
may not be the same as extracted.

1 DAC drives
384 PAs

1536 ant./3072 PAs



3rd Gen
RFIC



2nd Gen
5G Modem SoC

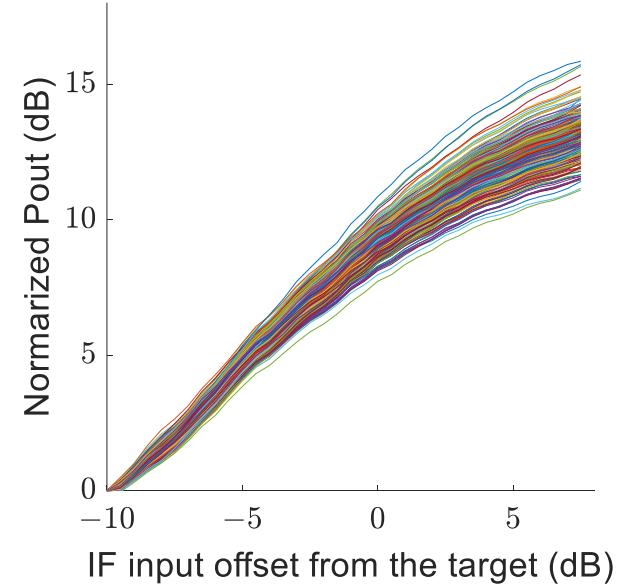
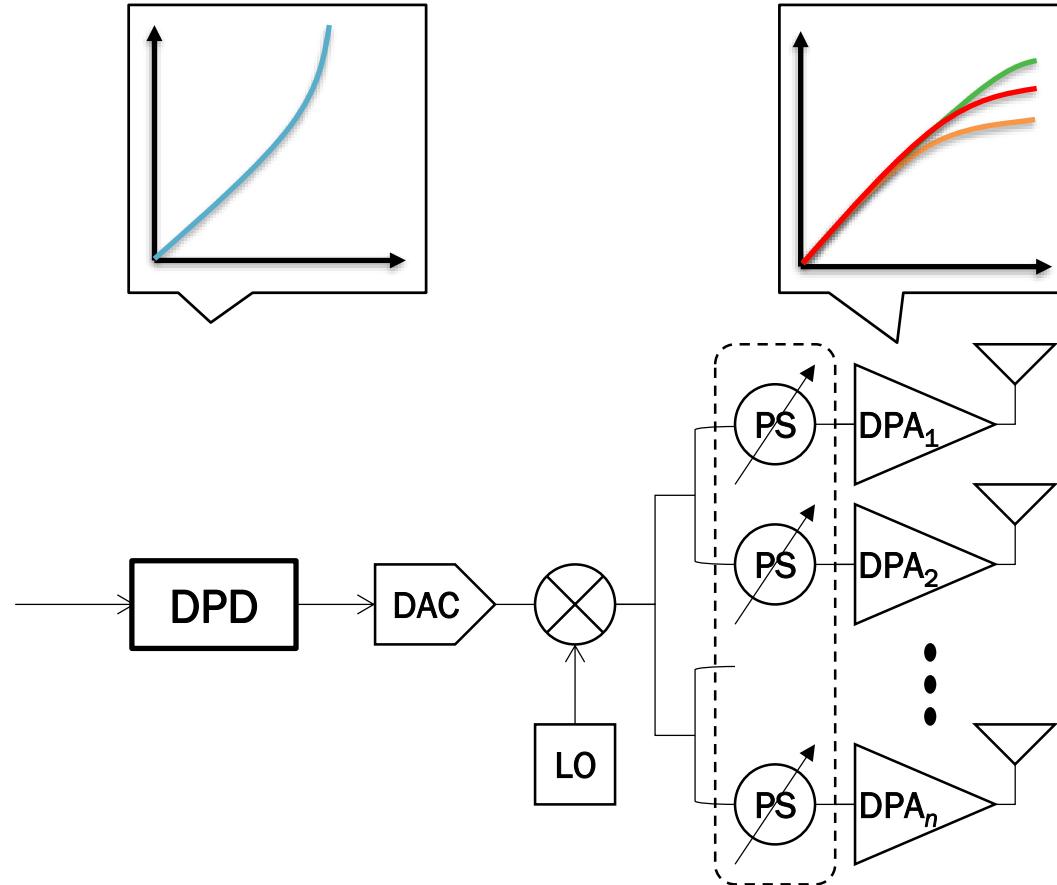


DFE RFIC Integrated Chip

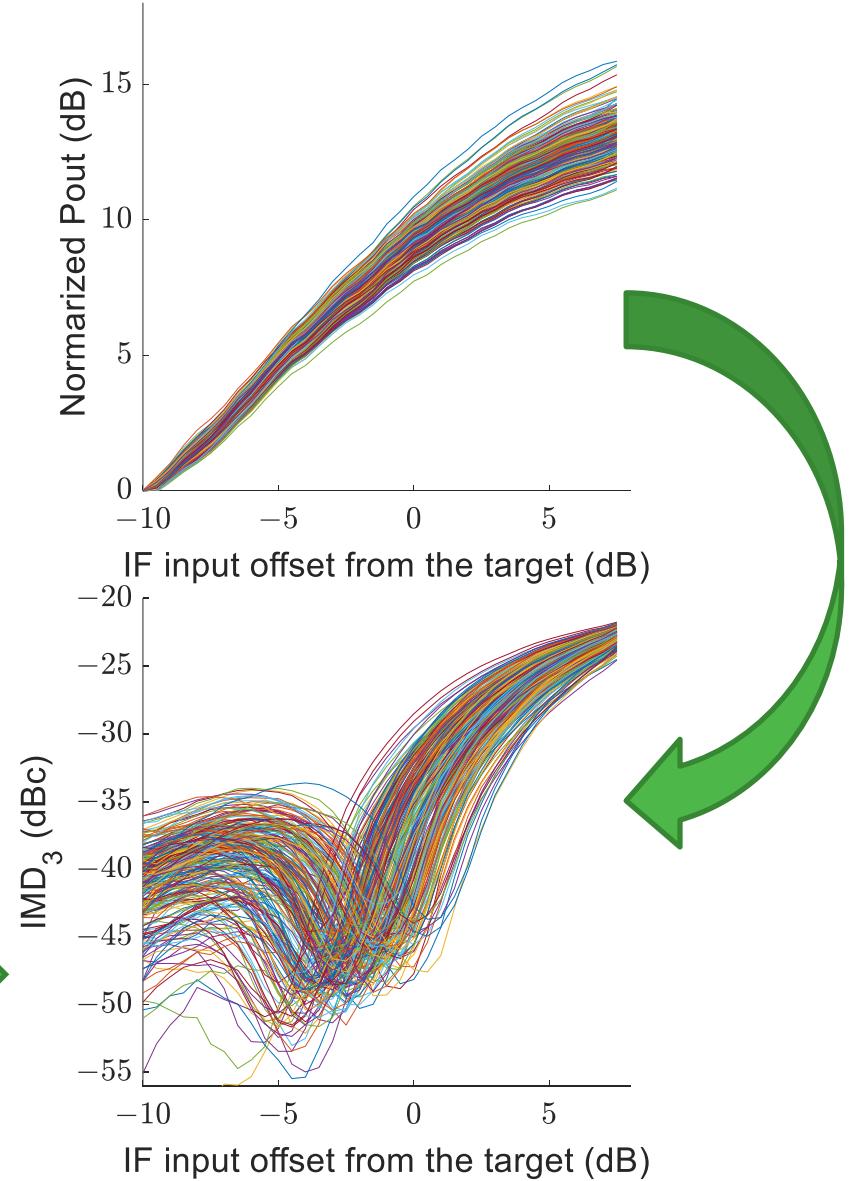
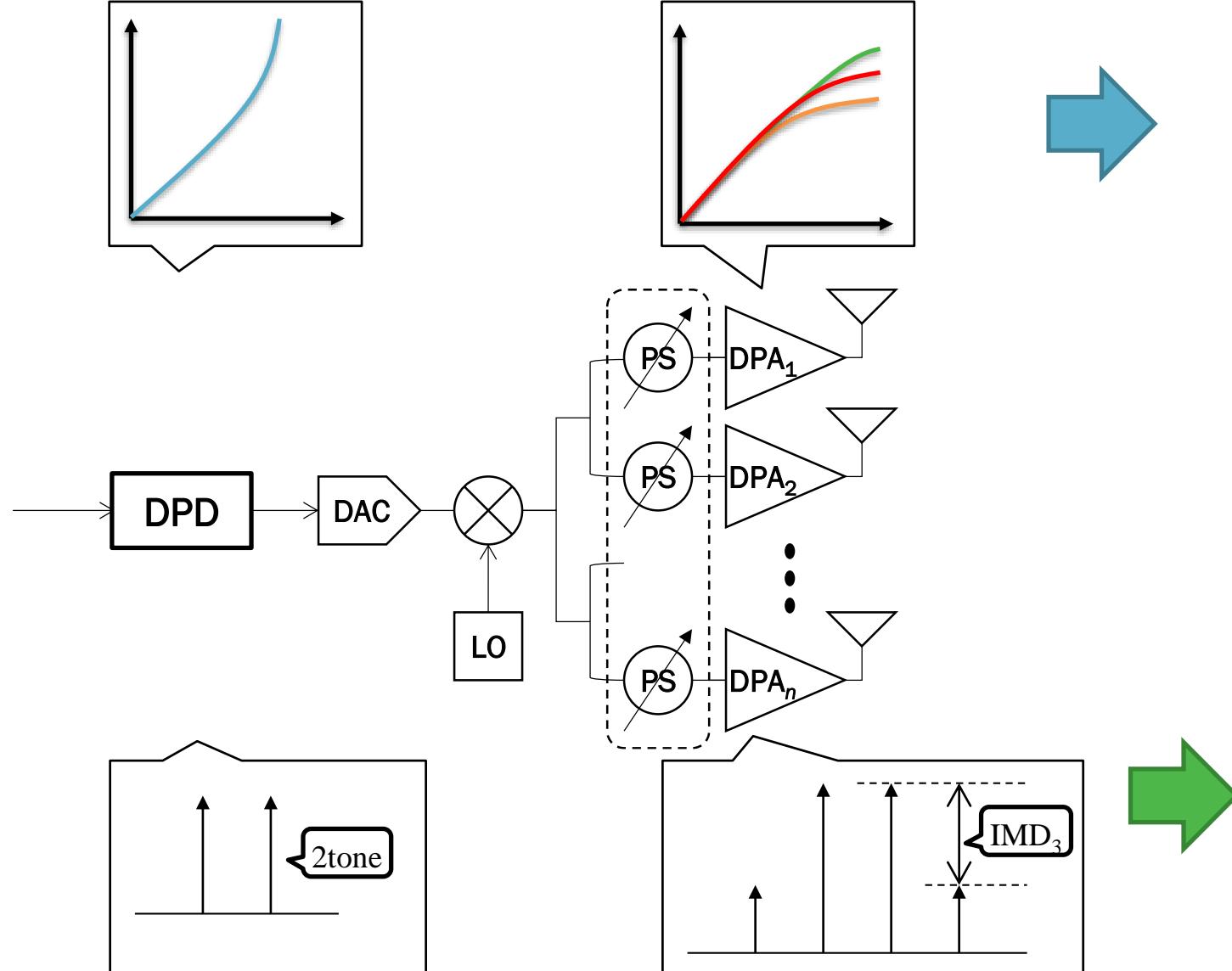


3rd Gen
Compact Macro

IEM as Pin-Pout Curve Variation

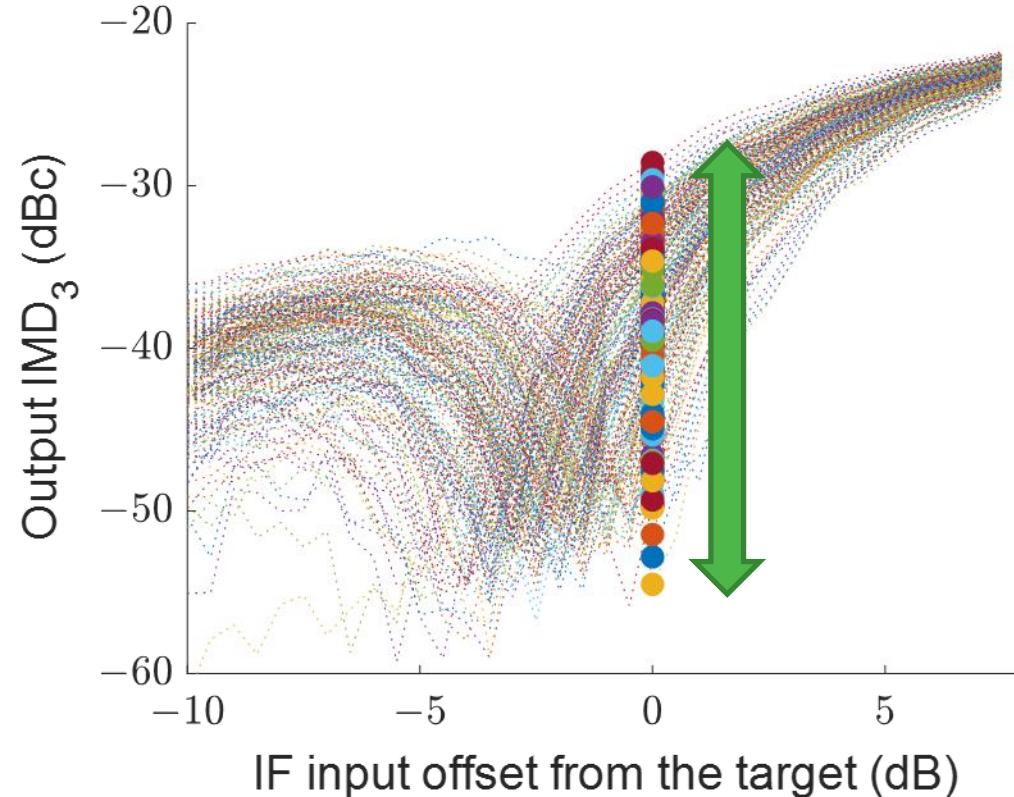


IEM as IMD₃ Variation

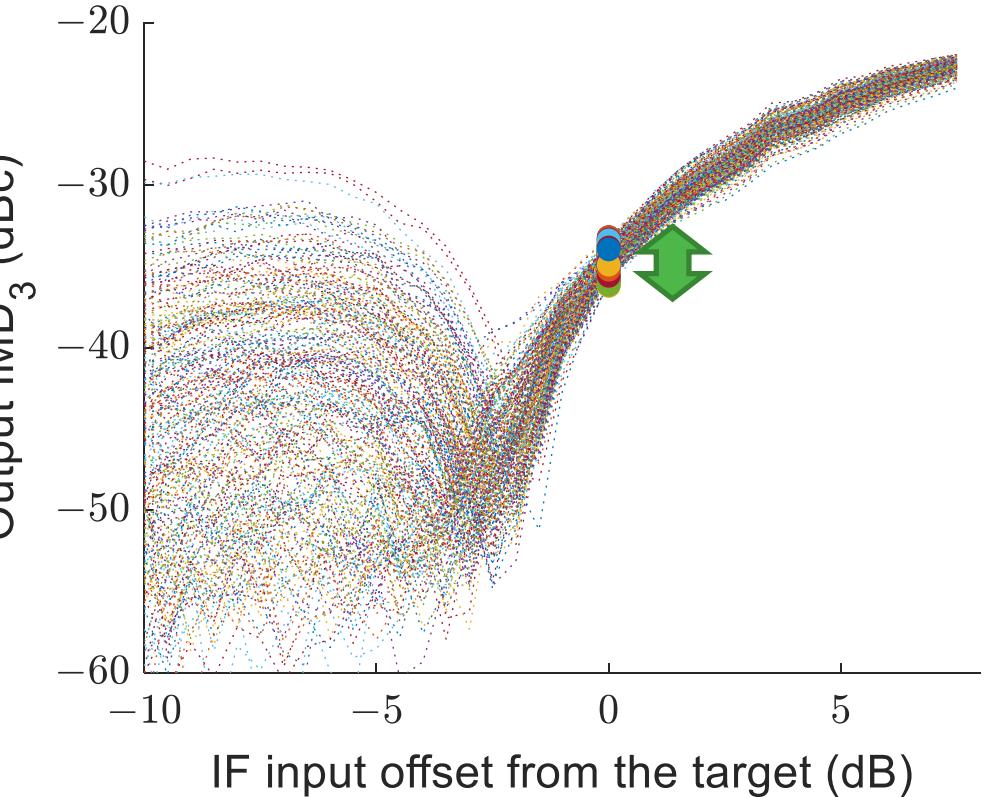


Motivation (1): IEM Compensation

w/o IEM compensation

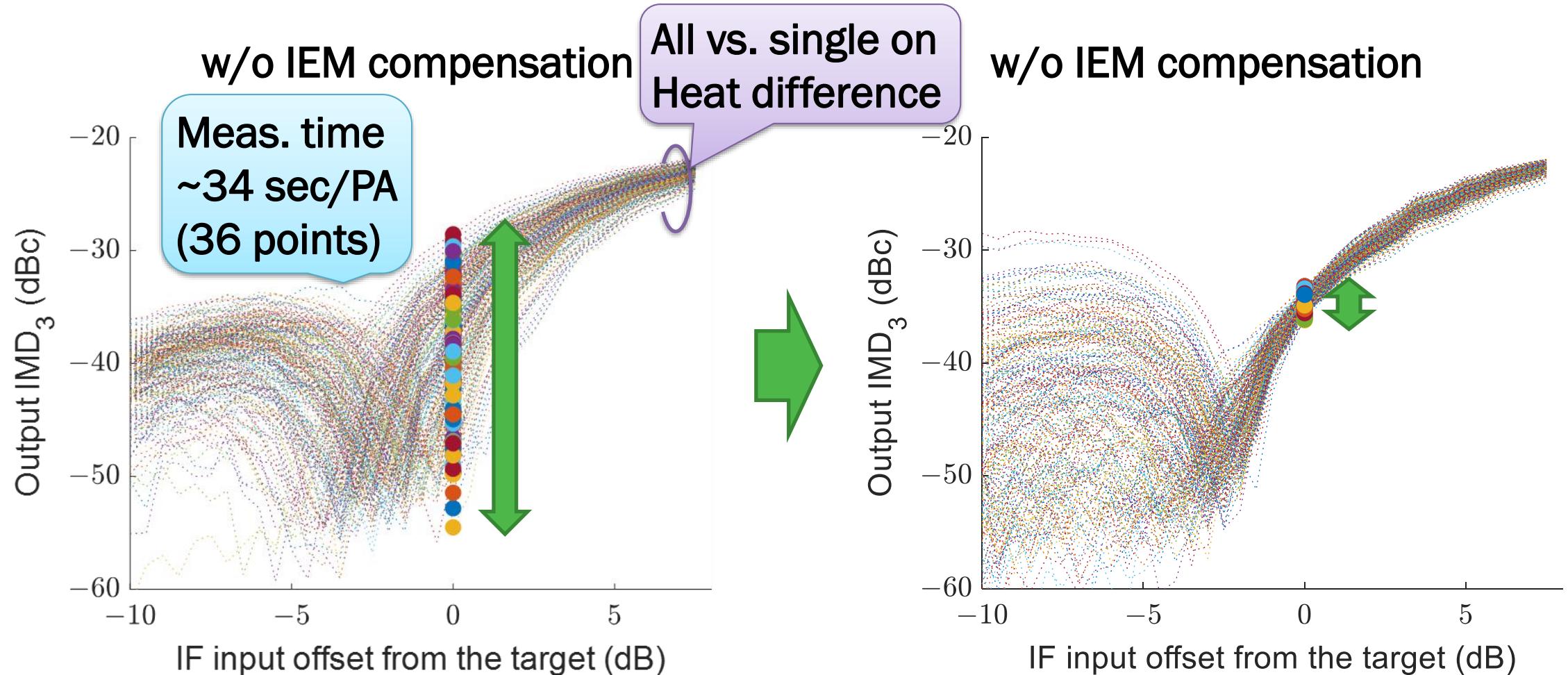


w/o IEM compensation



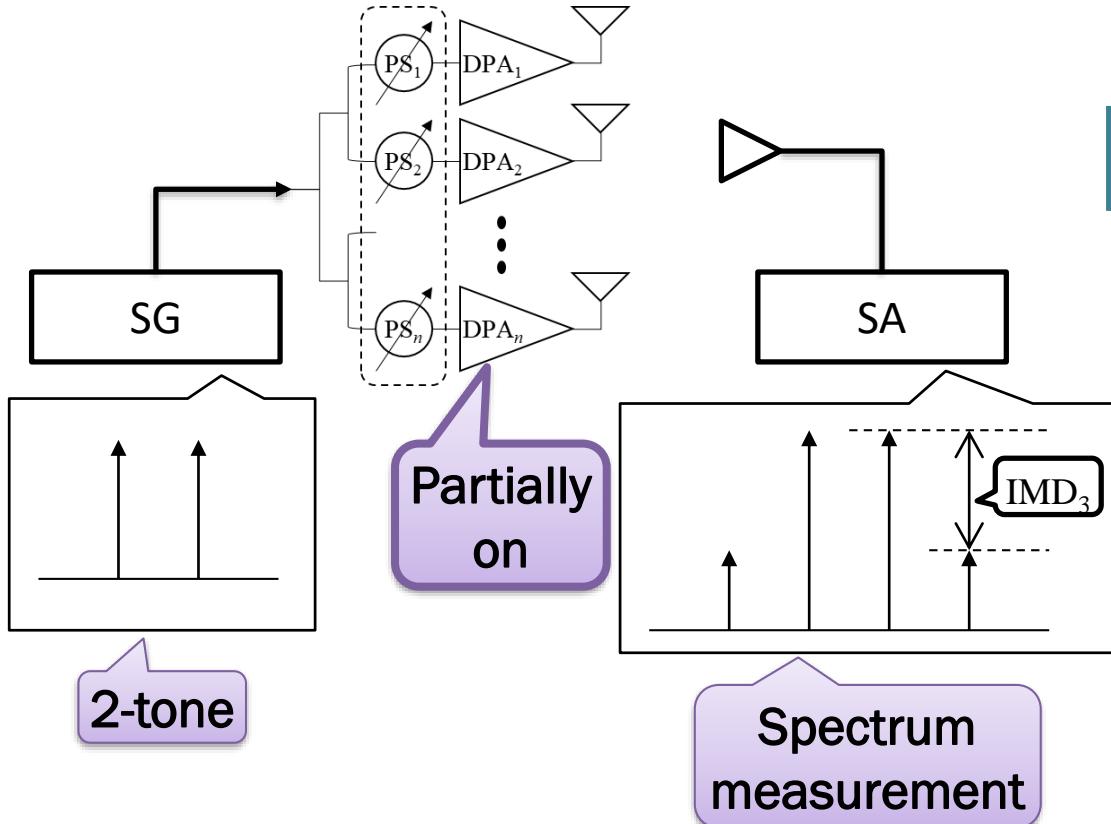
Match IMD_3 levels at the target input power

Motivation (1): IEM Compensation

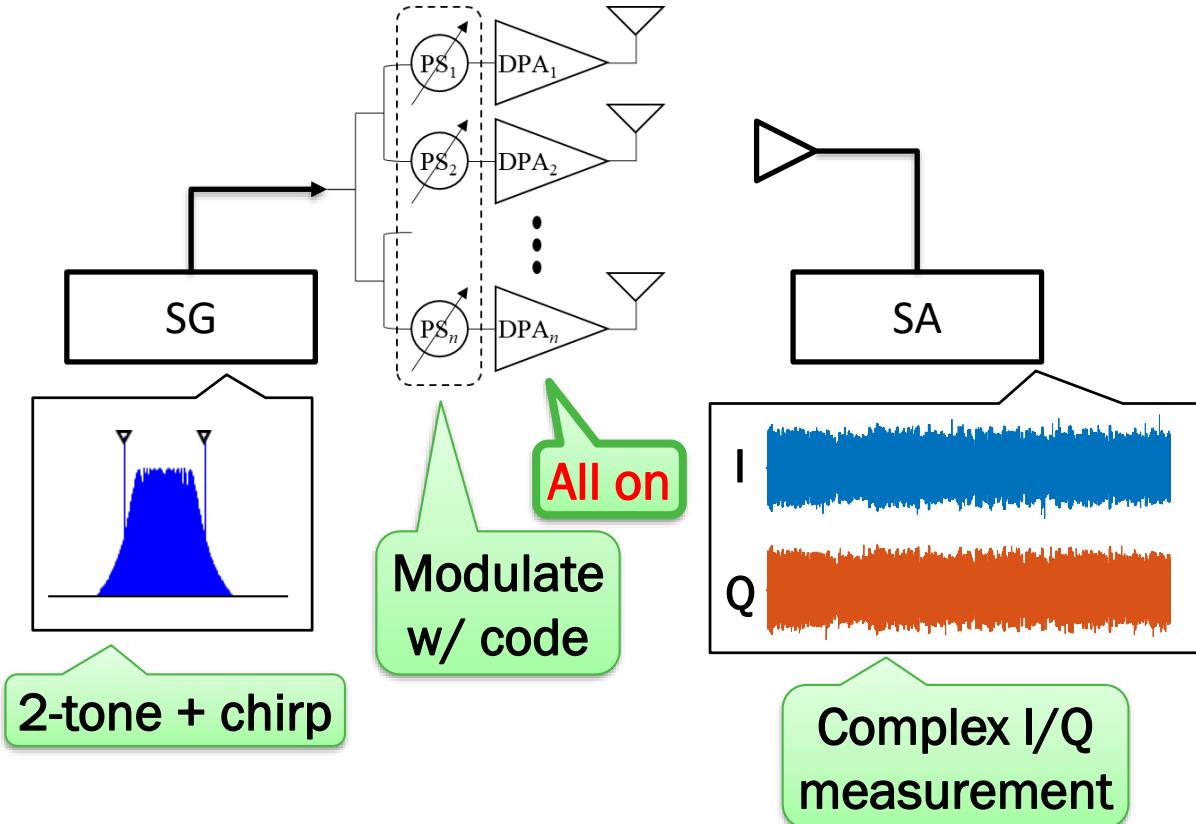


Match IMD₃ levels at the target input power

Conventional IM₃ measurement

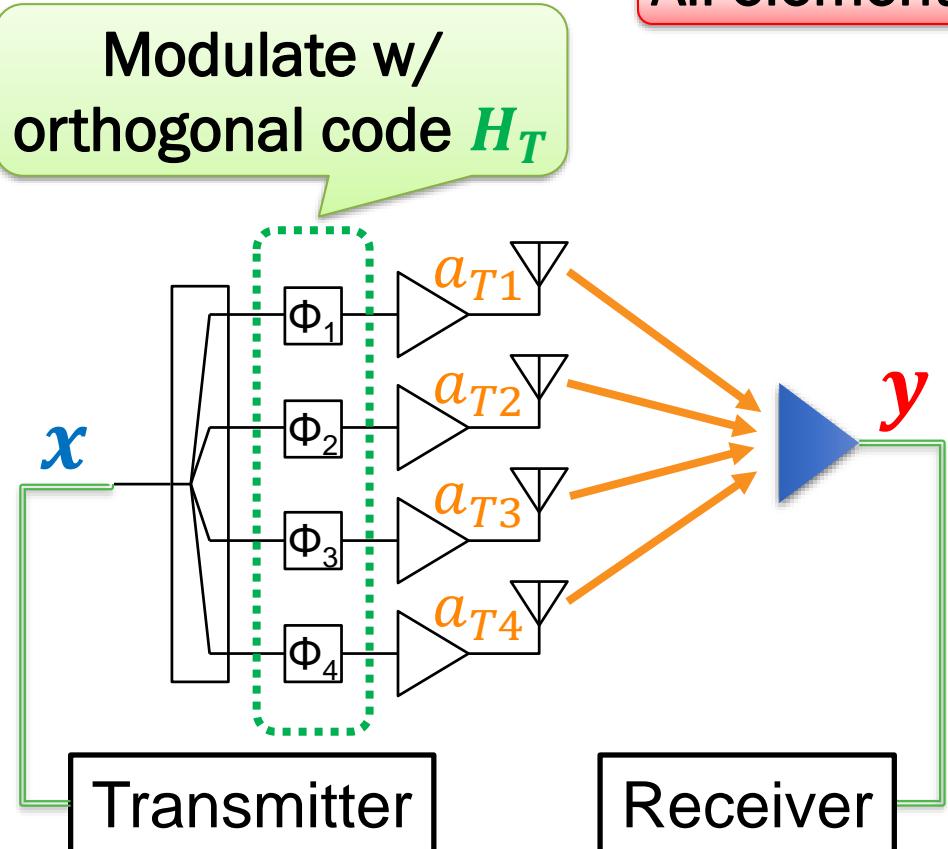


Fast simultaneous IM₃ measurement



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All elements are characterized simultaneously

$$y_1 = (+1 \cdot a_{T1} + j \cdot a_{T2} + j \cdot a_{T3} - 1 \cdot a_{T4}) \cdot x$$

$$y_2 = (+j \cdot a_{T1} + 1 \cdot a_{T2} - 1 \cdot a_{T3} + j \cdot a_{T4}) \cdot x$$

$$y_3 = (+j \cdot a_{T1} - 1 \cdot a_{T2} + 1 \cdot a_{T3} + j \cdot a_{T4}) \cdot x$$

$$y_4 = (-1 \cdot a_{T1} + j \cdot a_{T2} + j \cdot a_{T3} + 1 \cdot a_{T4}) \cdot x$$

Orthogonal code H_T

4-vector measurement

$$y = H_T \cdot A_T \cdot x$$

Gain/Phase of each element A_T

$$A_T = H_T^{-1} \cdot (y \cdot x^{-1})$$

Condition number of $H_T \rightarrow$ inaccuracy of solution A_T
 Orthogonal code: $\text{cond}(H_T) = 1$

Fast Measurement Example

Hadamard Matrix (commonly used)

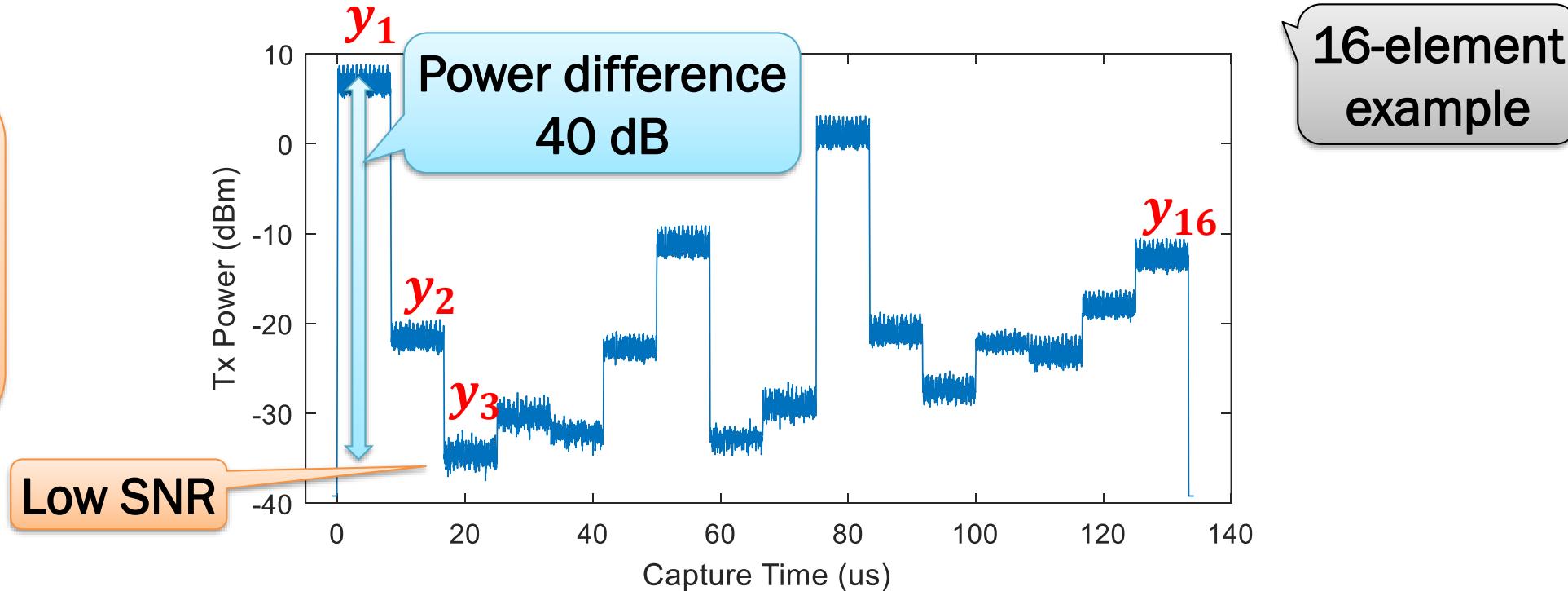
$$H_1 = 1, \quad H_{2^k} = \begin{bmatrix} H_{2^{k-1}} & H_{2^{k-1}} \\ H_{2^{k-1}} & -H_{2^{k-1}} \end{bmatrix}$$

Recursive for ($k = 0, 1, 2 \dots$)

IM₃ is 30~50 dB lower than 2-tone
(IM₃ of y_3 is 70~90 dB lower than mean y_1)

Single Capture

$$\left\{ \begin{array}{l} y_1 = H_{16\text{row}1} \cdot A_T \cdot x \\ y_2 = H_{16\text{row}2} \cdot A_T \cdot x \\ \vdots \\ y_{16} = H_{16\text{row}16} \cdot A_T \cdot x \end{array} \right.$$



Hadamard Matrix

(commonly used, first row issue exists)

$$H_1 = 1, \quad H_{2^k} = \begin{bmatrix} H_{2^{k-1}} & H_{2^{k-1}} \\ H_{2^{k-1}} & -H_{2^{k-1}} \end{bmatrix}$$

Recursive for ($k = 0, 1, 2 \dots$)

| | | | | | | | | | | | | | | | |
|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 16 |
| 1 | -1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | 0 |
| 1 | 1 | -1 | -1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | 1 | 1 | -1 | -1 | 0 |
| 1 | -1 | -1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | 1 | 1 | -1 | -1 | 1 | 0 |
| 1 | 1 | 1 | 1 | -1 | -1 | -1 | 1 | 1 | 1 | 1 | -1 | -1 | -1 | -1 | 0 |
| 1 | -1 | 1 | -1 | -1 | 1 | 1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | 1 | 0 |
| 1 | 1 | -1 | -1 | -1 | 1 | 1 | 1 | 1 | -1 | -1 | -1 | 1 | 1 | 1 | 0 |
| 1 | -1 | -1 | 1 | 1 | 1 | -1 | 1 | -1 | -1 | 1 | 1 | -1 | 1 | -1 | 0 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | -1 | -1 | -1 | -1 | -1 | 1 | 1 | -1 | 0 |
| 1 | -1 | 1 | -1 | 1 | -1 | -1 | 1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | 0 |
| 1 | 1 | -1 | 1 | 1 | -1 | -1 | -1 | 1 | 1 | -1 | -1 | 1 | 1 | 1 | 0 |
| 1 | -1 | -1 | 1 | 1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | 0 |
| 1 | 1 | 1 | 1 | -1 | -1 | -1 | -1 | 1 | 1 | 1 | 1 | -1 | 1 | 1 | 0 |
| 1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 | -1 | 1 | -1 | 1 | 1 | -1 | 0 |
| 1 | 1 | -1 | 1 | 1 | -1 | -1 | -1 | 1 | 1 | -1 | -1 | 1 | 1 | 1 | 0 |
| 1 | -1 | -1 | 1 | 1 | 1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 | -1 | 0 |
| 1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | 1 | 1 | 1 | 0 |
| 1 | -1 | 1 | -1 | -1 | 1 | 1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 | -1 | 0 |

1st: 16
2nd~: 0

Sums of rows
For H_{16}

All 4
no 1st row issue

Proposed Code

$$H_{4^k} = \begin{bmatrix} H_{4^{k-1}} & H_{4^{k-1}} & H_{4^{k-1}} & -H_{4^{k-1}} \\ H_{4^{k-1}} & H_{4^{k-1}} & -H_{4^{k-1}} & H_{4^{k-1}} \\ H_{4^{k-1}} & -H_{4^{k-1}} & H_{4^{k-1}} & H_{4^{k-1}} \\ -H_{4^{k-1}} & H_{4^{k-1}} & H_{4^{k-1}} & H_{4^{k-1}} \end{bmatrix}$$

| | | | | | | | | | | | | | | | |
|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 4 | 1 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | -1 | -1 | 1 |
| 4 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | 1 | -1 | -1 | 1 |
| 4 | 1 | -1 | 1 | 1 | 1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 | -1 | 1 | -1 |
| 4 | -1 | 1 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 | -1 |
| 4 | 1 | 1 | 1 | -1 | 1 | 1 | -1 | -1 | -1 | 1 | 1 | 1 | 1 | 1 | -1 |
| 4 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | 1 | -1 | -1 | 1 | -1 | 1 | 1 | -1 |
| 4 | 1 | -1 | 1 | 1 | 1 | -1 | 1 | 1 | -1 | -1 | 1 | -1 | 1 | -1 | 1 |
| 4 | -1 | 1 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | -1 | 1 | -1 | -1 | 1 | 1 |
| 4 | 1 | 1 | 1 | -1 | 1 | 1 | -1 | -1 | -1 | 1 | 1 | 1 | -1 | 1 | -1 |
| 4 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | 1 | -1 | -1 | 1 | -1 | 1 | -1 | 1 |
| 4 | 1 | -1 | 1 | 1 | 1 | -1 | 1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | 1 |
| 4 | -1 | 1 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | -1 | 1 | -1 | -1 | 1 | 1 |
| 4 | 1 | 1 | 1 | -1 | -1 | -1 | -1 | 1 | 1 | 1 | 1 | -1 | 1 | 1 | -1 |
| 4 | 1 | 1 | -1 | -1 | 1 | -1 | -1 | 1 | 1 | 1 | -1 | 1 | 1 | -1 | 1 |
| 4 | 1 | -1 | -1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 |
| 4 | -1 | -1 | -1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 |
| 4 | -1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 |
| 4 | -1 | 1 | -1 | -1 | 1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 |
| 4 | 1 | -1 | -1 | -1 | 1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 |

[1] Y. Aoki *et al.*, "Fast Characterization of Phased-Array Elements Using Orthogonal Codes," (T-MTT 2023)

Hadamard Matrix

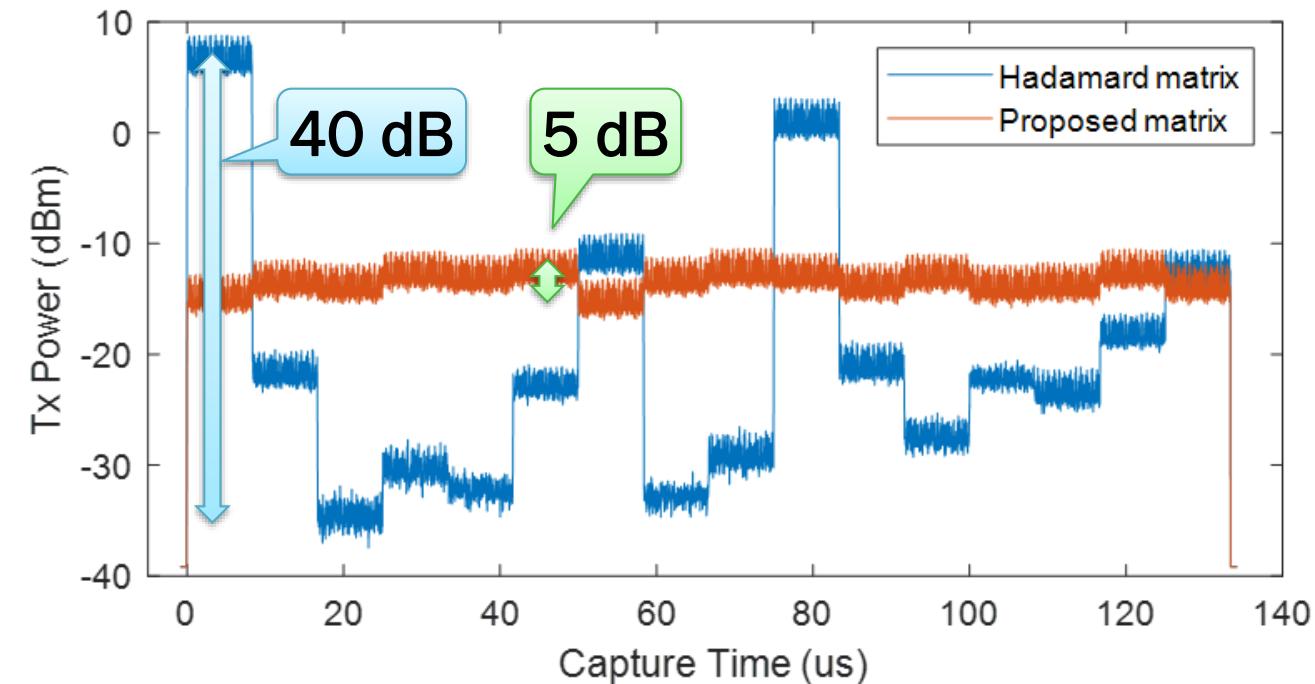
(commonly used)

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Recursive for ($k = 0, 1, 2 \dots$)

Proposed Code

$$H_{4^k} = \begin{bmatrix} H_{4^{k-1}} & H_{4^{k-1}} & H_{4^{k-1}} & -H_{4^{k-1}} \\ H_{4^{k-1}} & H_{4^{k-1}} & -H_{4^{k-1}} & H_{4^{k-1}} \\ H_{4^{k-1}} & -H_{4^{k-1}} & H_{4^{k-1}} & H_{4^{k-1}} \\ -H_{4^{k-1}} & H_{4^{k-1}} & H_{4^{k-1}} & H_{4^{k-1}} \end{bmatrix}$$



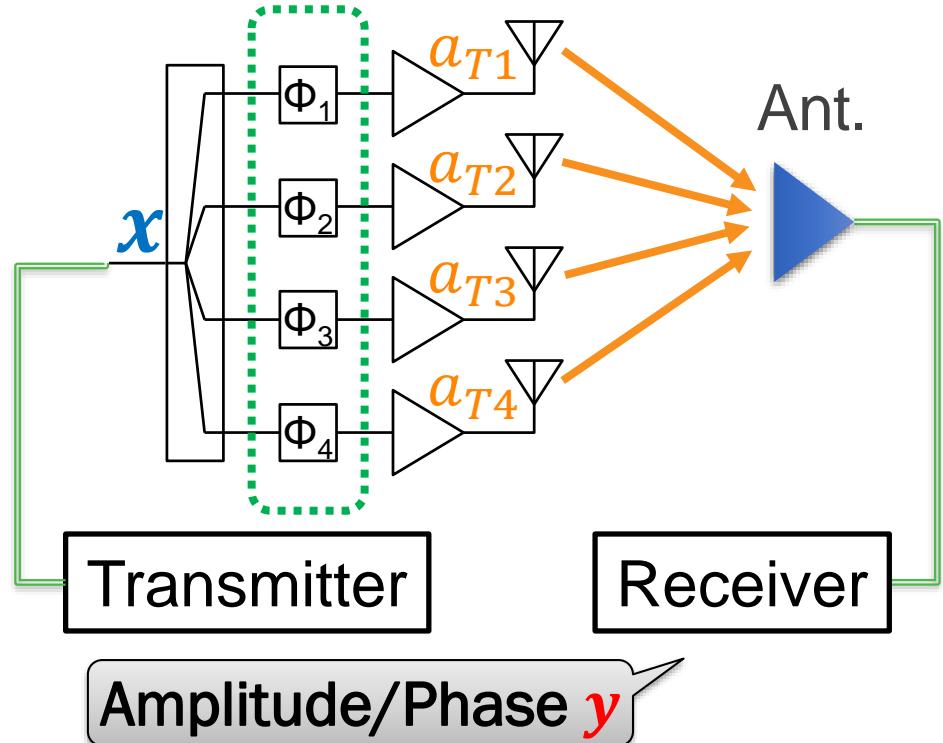
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PAA IMD₃ w/ Orthogonal Code

Same as fast PAA calibration
w/ orthogonal code

Characterize IMD at the same time



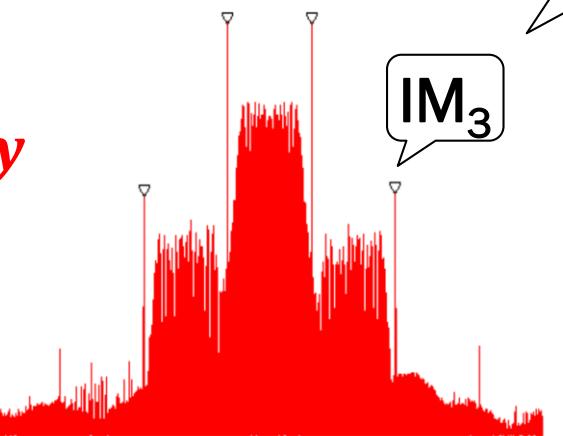
Orthogonal codes H_T

$$y = H_T \cdot A_T \cdot x$$

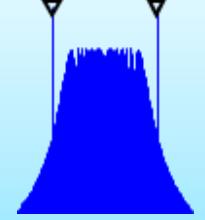
Amplitude/Phase
of each path A_T

2-tone+chirp

Output y



Input x
2-tone
+chirp



How to solve for
Amplitude/Phase
of IMD₃?



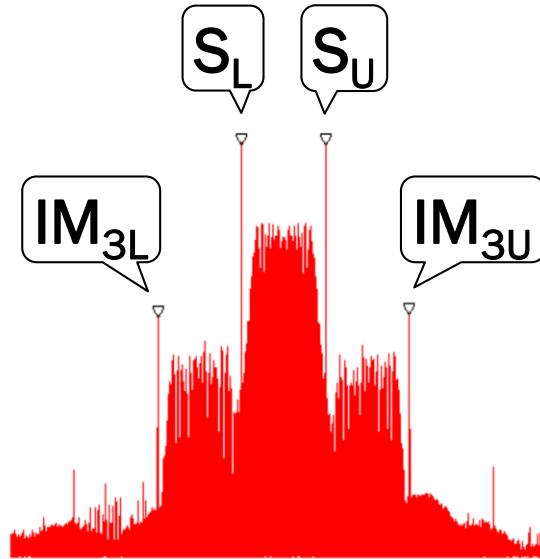
Use IMD₃'s relative
Amplitude/Phase
from 2-tone

[1] Y. Aoki *et al.*, “Fast Characterization of Phased-Array Elements Using Orthogonal Codes,” (T-MTT 2023)

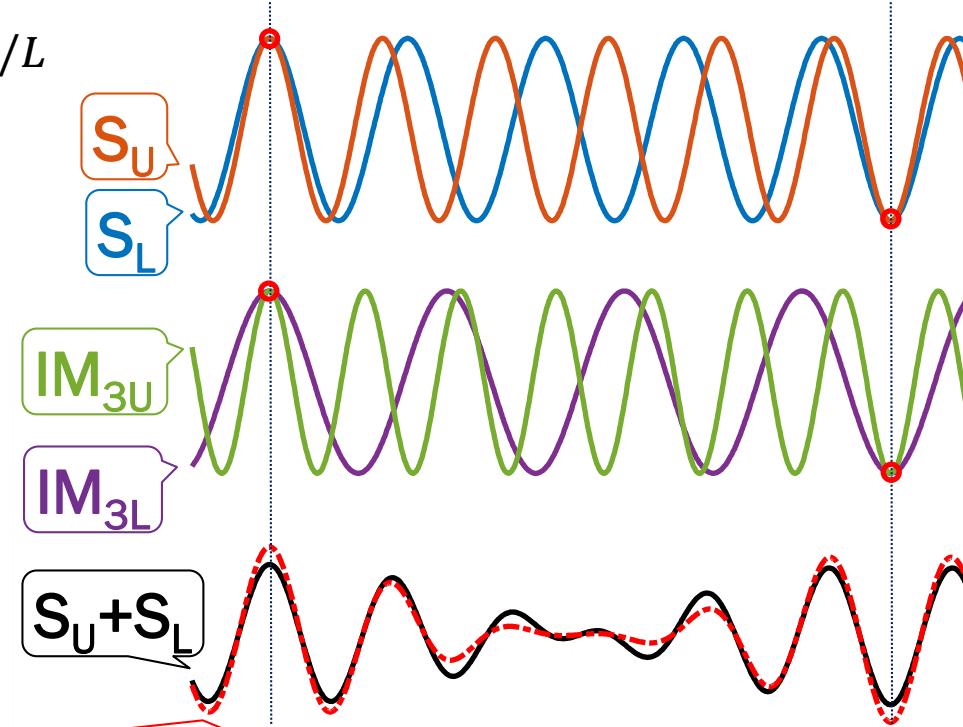
Definition

$$\varphi_{IMD} = \angle IM_{U/L} - \angle S_{U/L}$$

when $\angle S_L = \angle S_U$

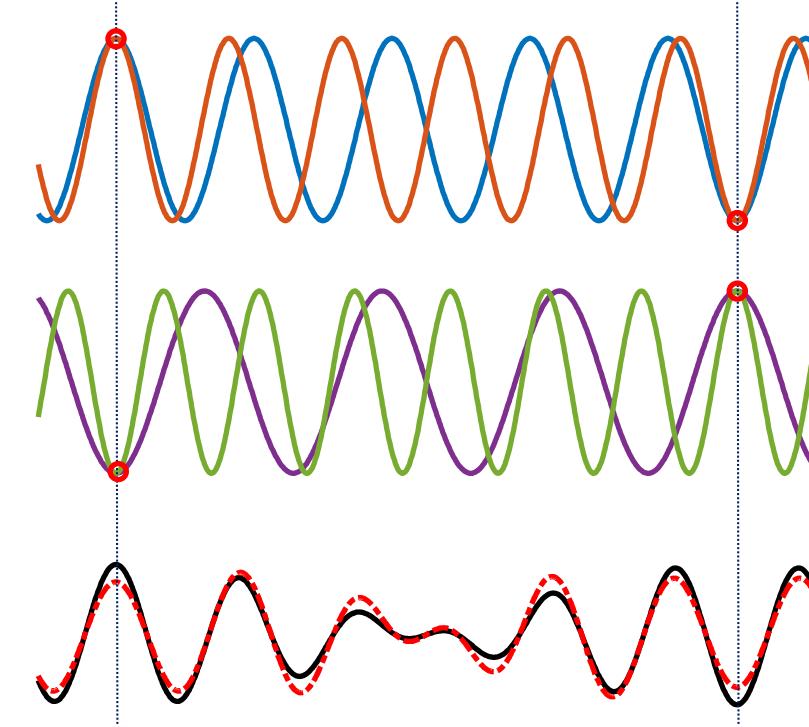


Gain-expansion



In-phase
($\varphi_{IMD} = 0^\circ$)

Gain-compression



Out-phase
($\varphi_{IMD} = 180^\circ$)

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Gain/Phase of PAA elements

$$A_T = H_T^{-1} \cdot (\underline{y} \cdot \underline{x}^{-1})$$



2-tone ampl/phase
for each phase code

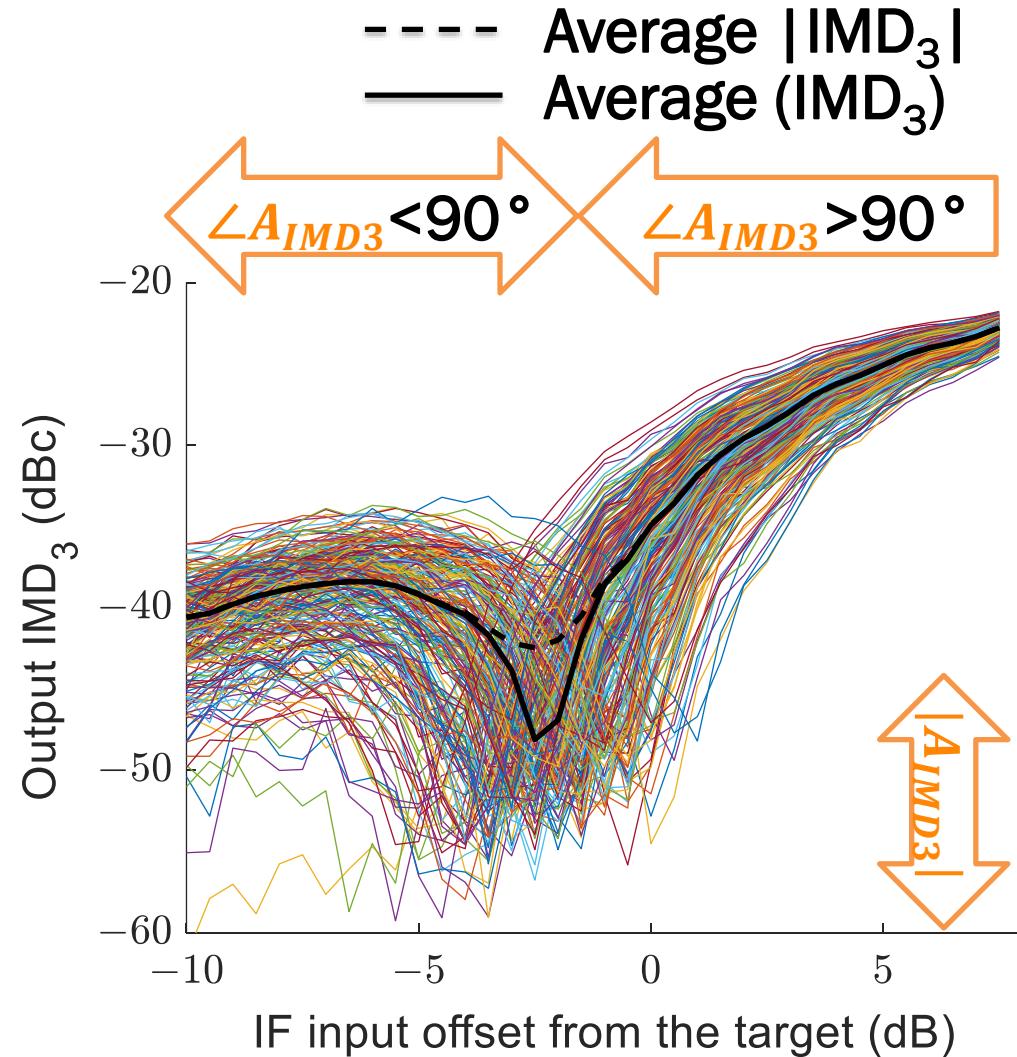
$$A_{IM3} = H_T^{-1} \cdot (\underline{y}_{IM3} \cdot \underline{x}^{-1})$$

Relative ampl/phase
of IMD₃ (IMD₃)

IMD₃ ampl/phase
for each phase code

$$A_{IMD3} = A_{IM3} \oslash A_T$$

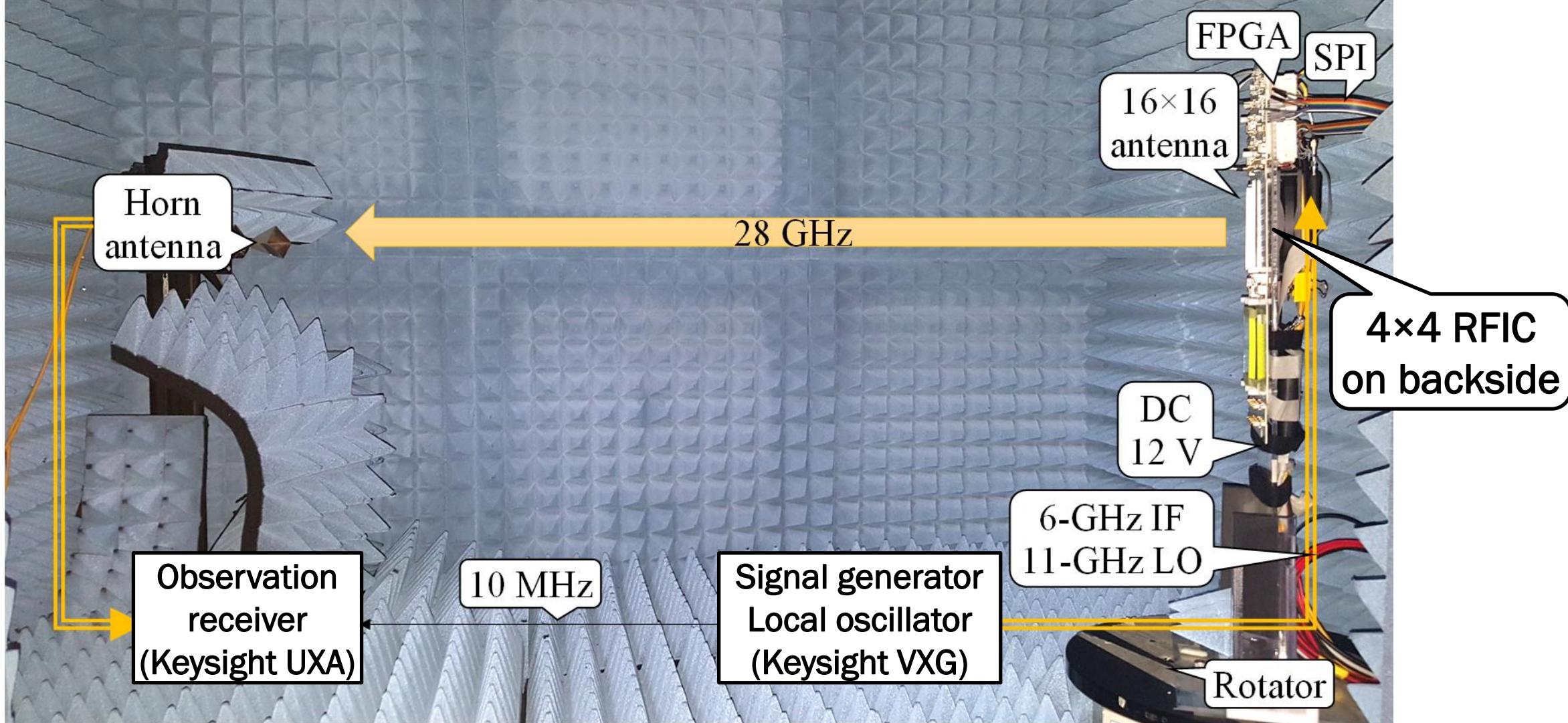
Element wise division



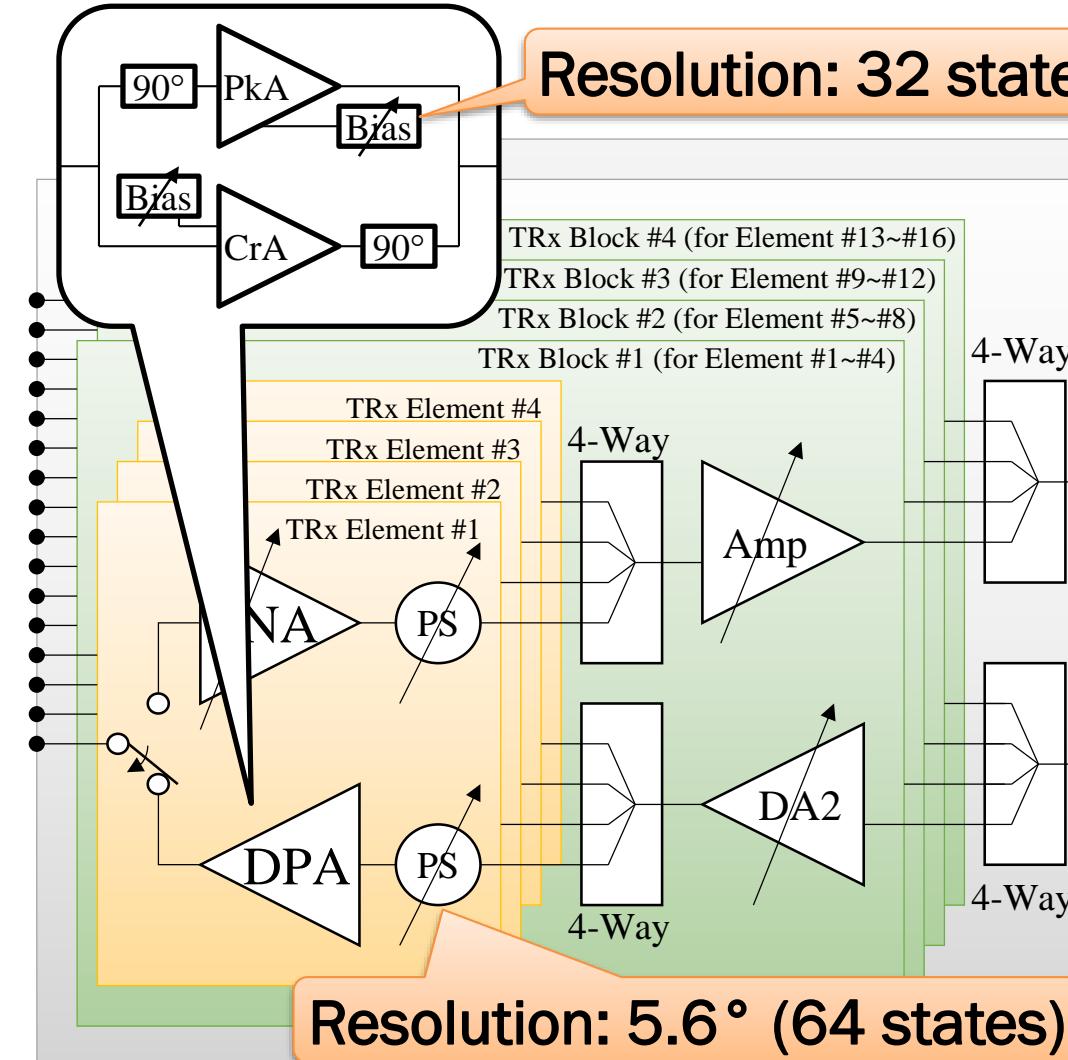
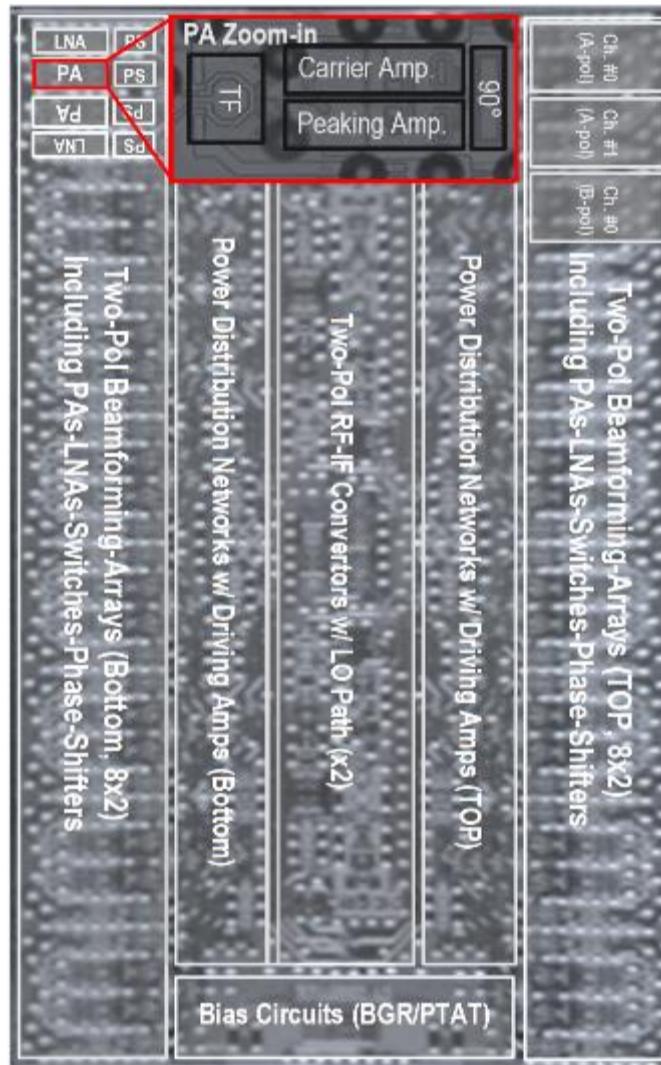
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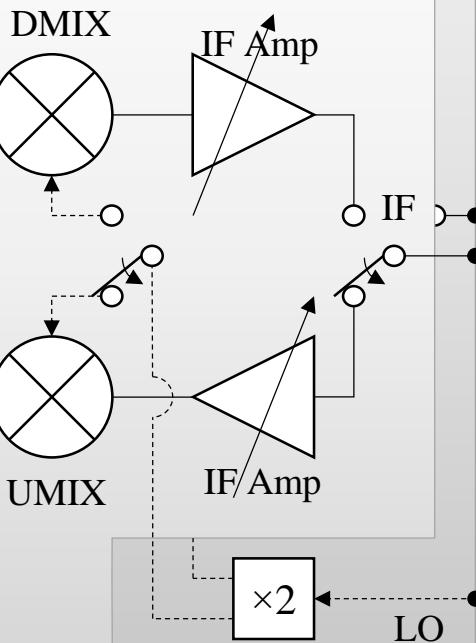
16×16 PAA Test Board



28-GHz 2×16-TRx-Element RFIC

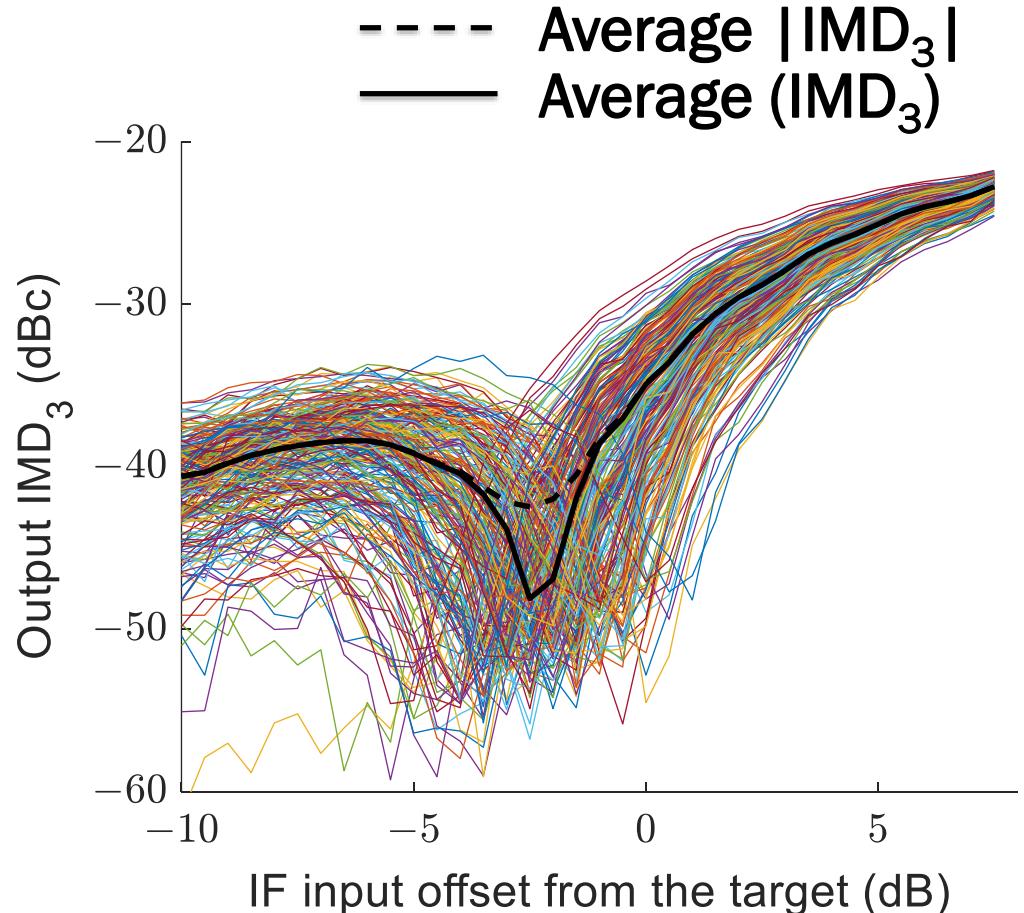
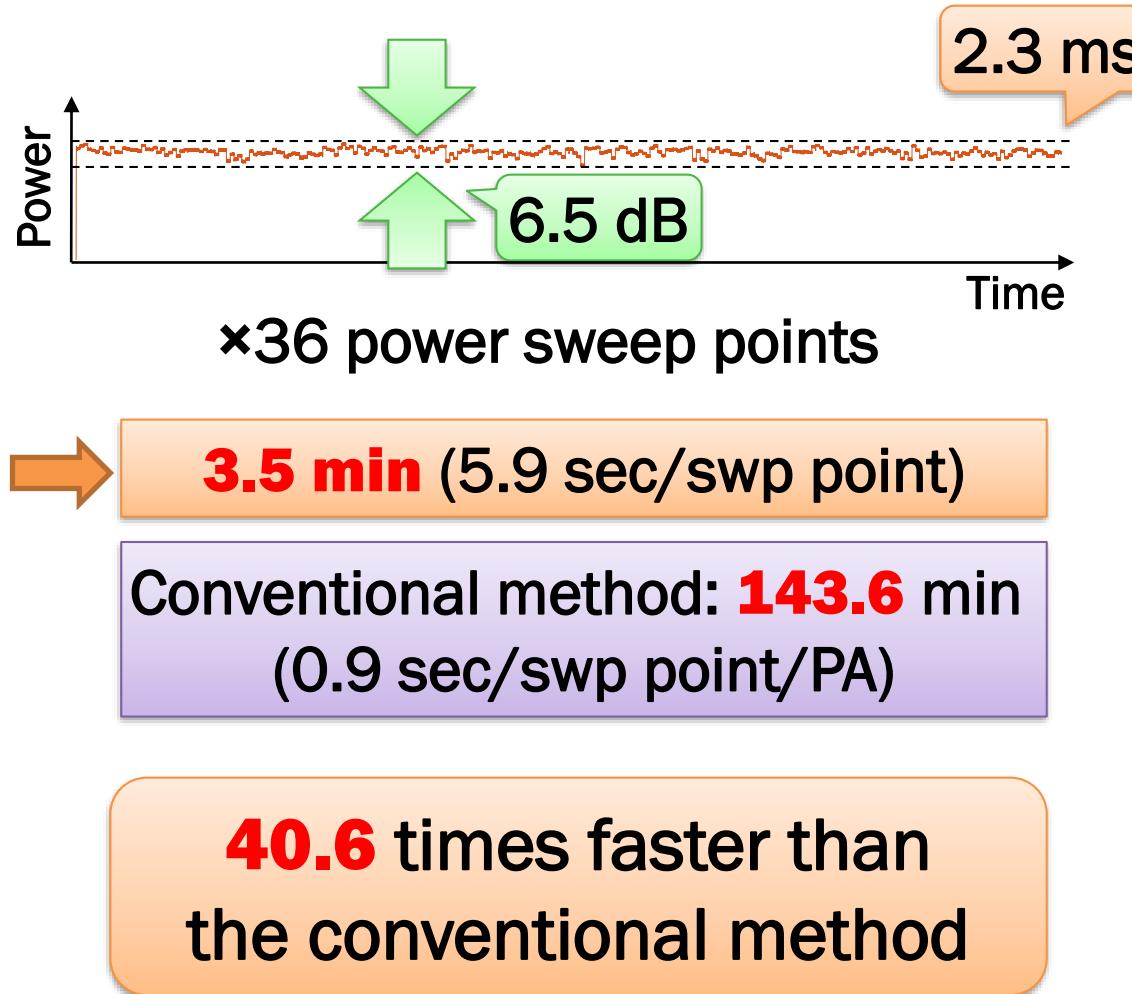


28-GHz x16 Hpol Transceiver
28-GHz x16 Vpol Transceiver

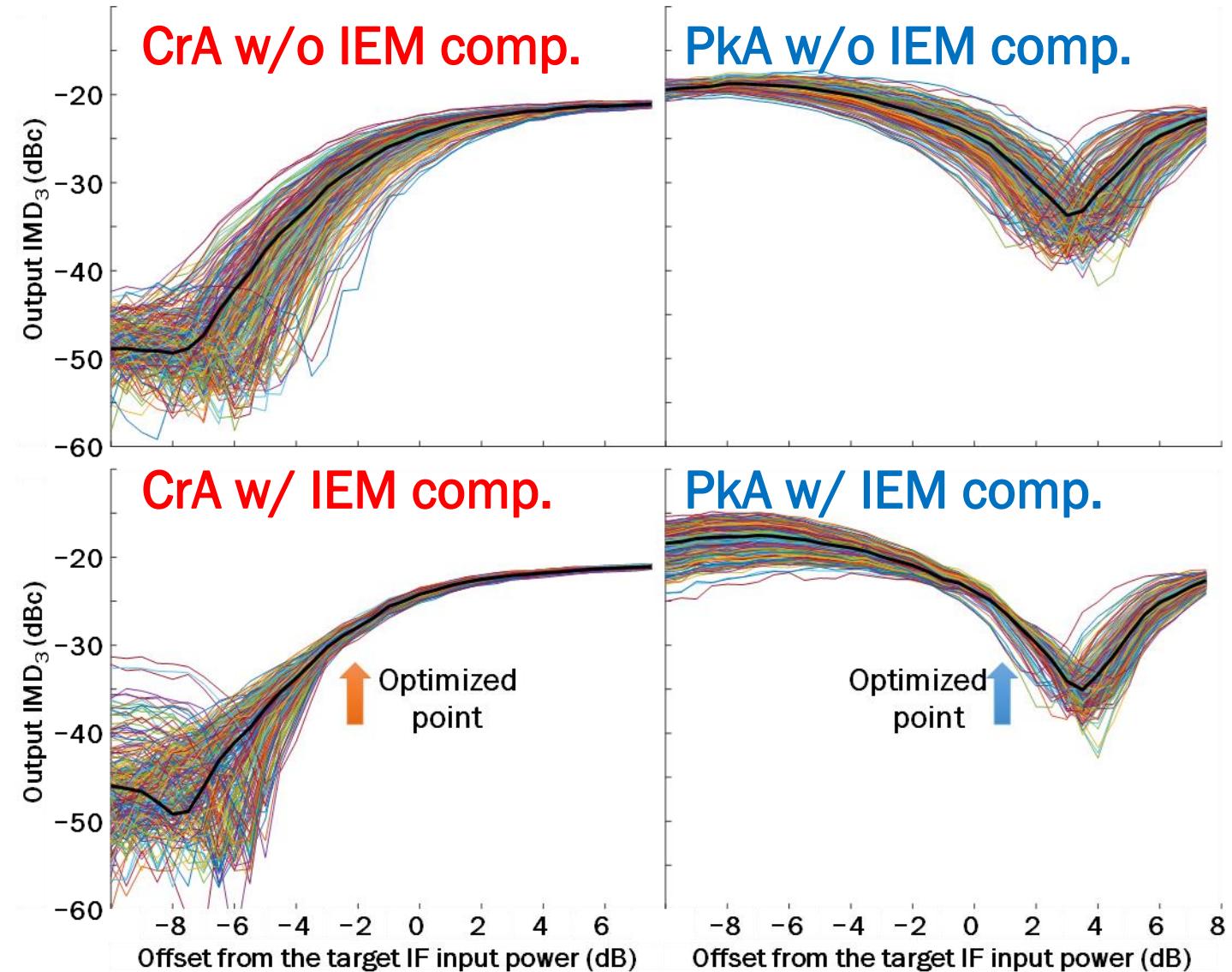
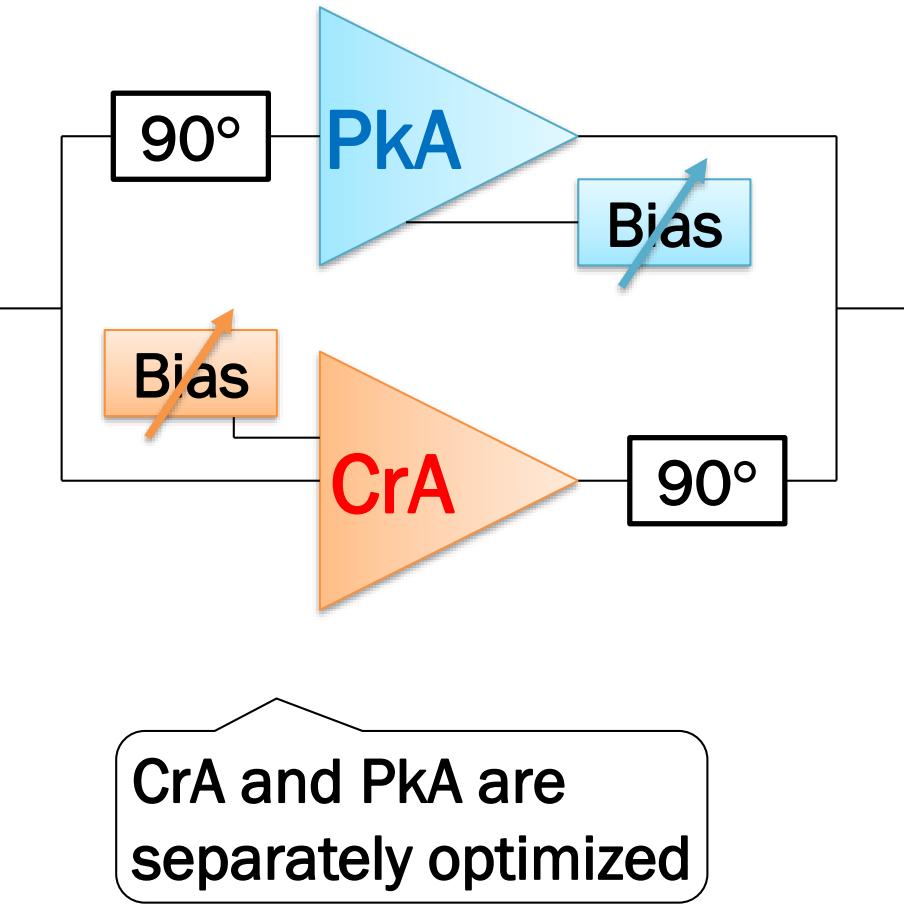


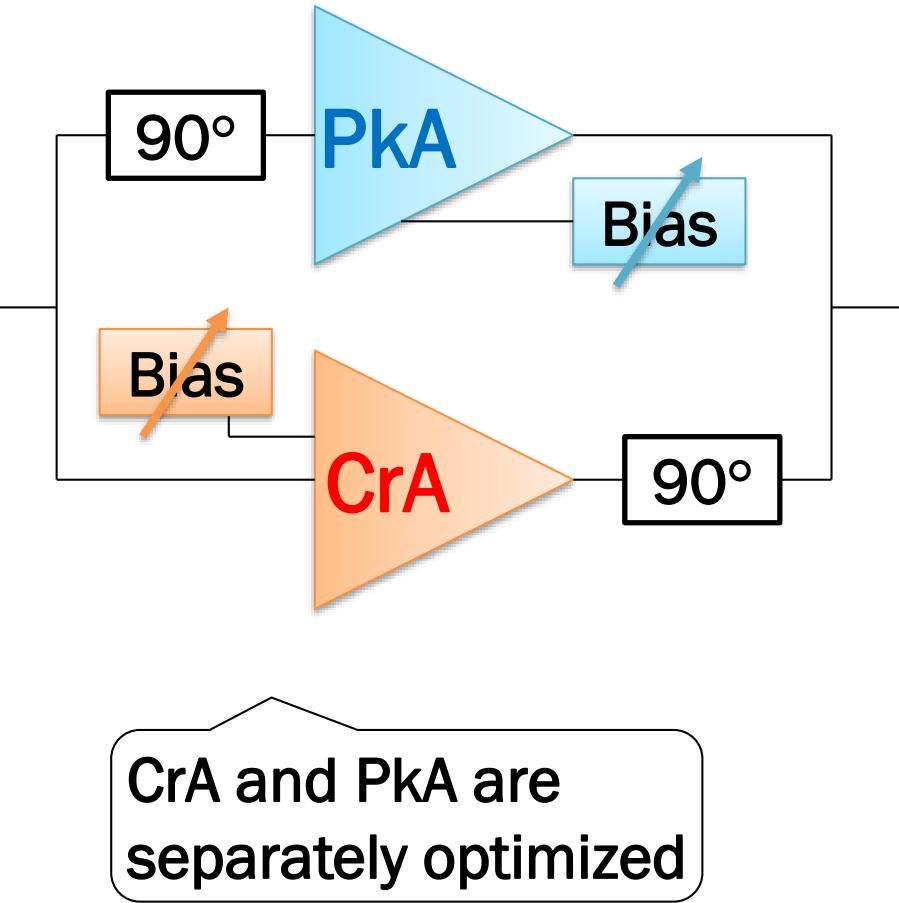
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Measurement Time

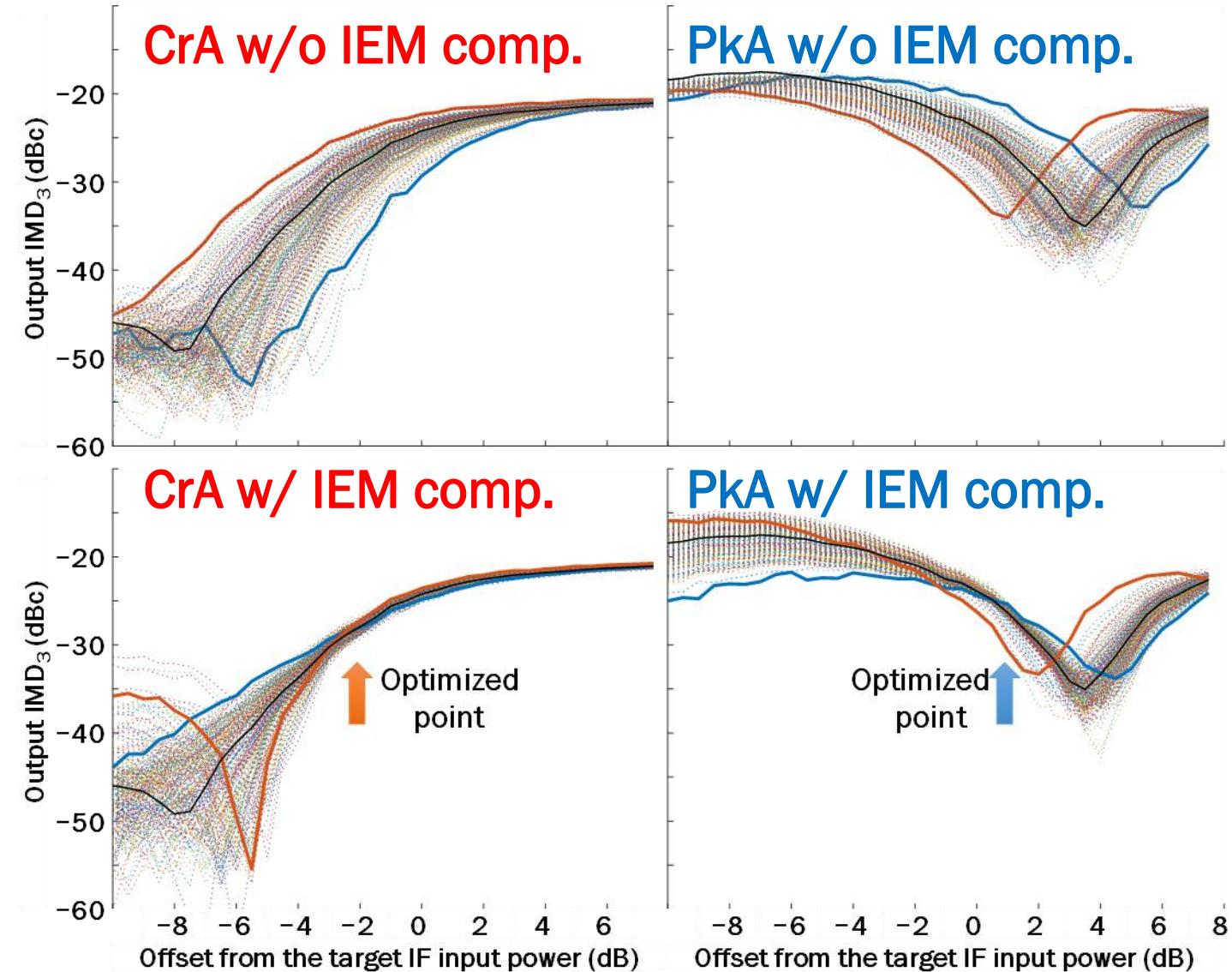


IEM Compensation



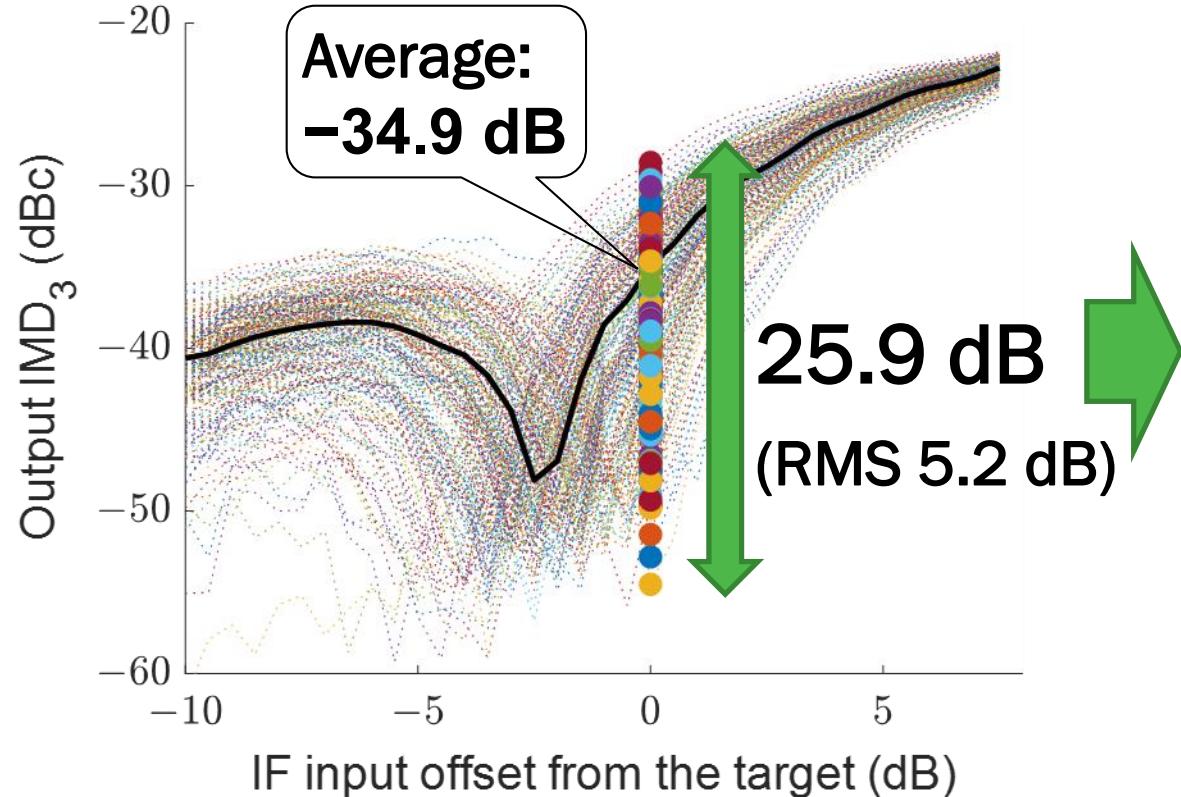


IEM Compensation

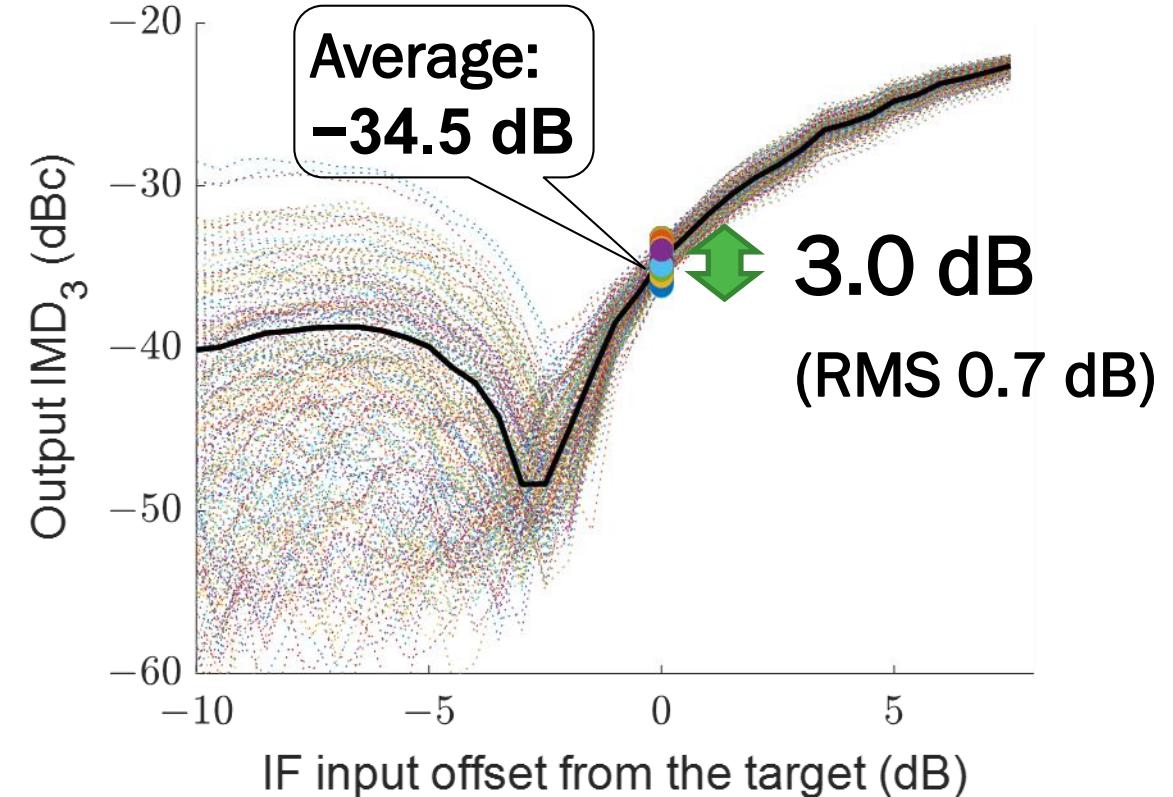


IEM Compensation Result

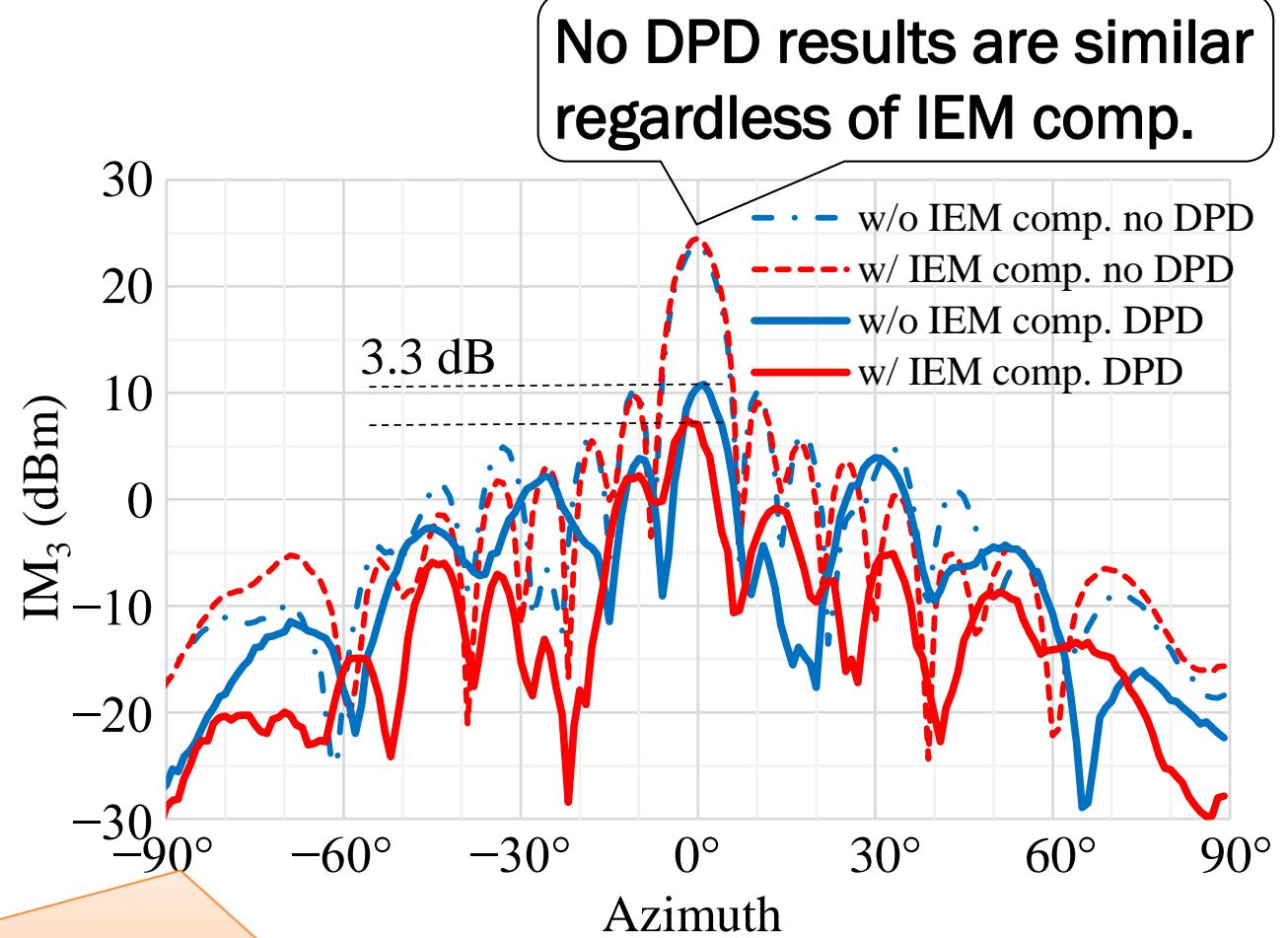
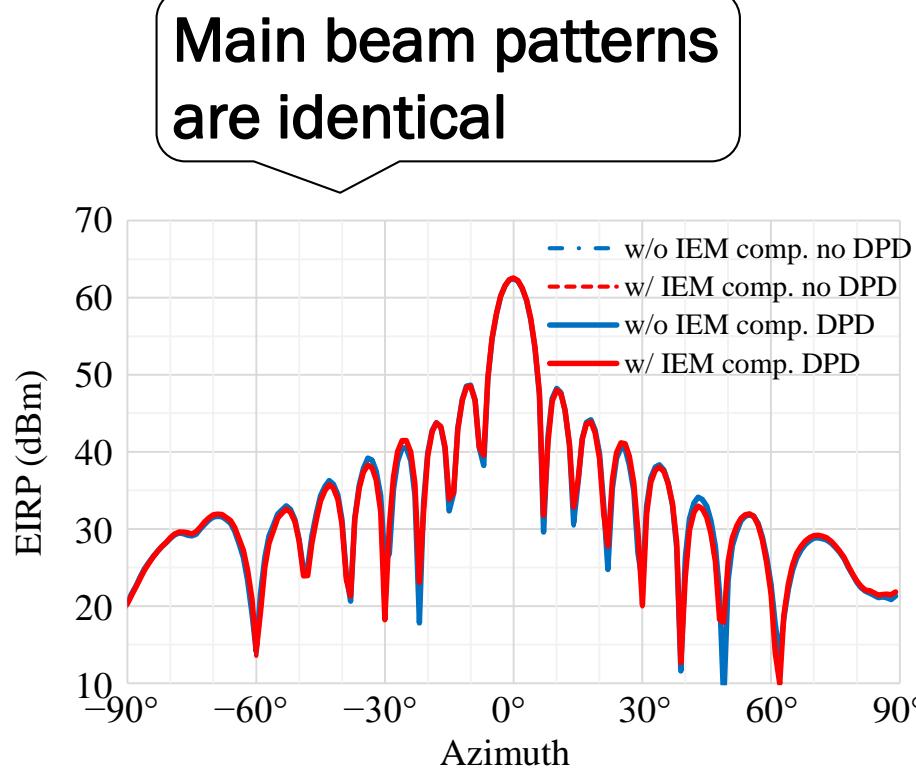
w/o IEM compensation



w/o IEM compensation



Beam Pattern and IM_3 Radiation



3.3 dB lower IM_3 for DPD with IEM compensation.
Also, it has lower IM_3 emission in $\pm 30^\circ \sim 60^\circ$ range

Summary

- Fast inter-element mismatch compensation technique for phased-array beamformers is demonstrated
- 256 PAs are measured simultaneously using 2-tone+chirp signal modulated with proposed orthogonal code
- The proposed method can characterize IMD_3 40 times faster than the conventional method
- RMS IMD_3 variation is suppressed from 5.2 dB to 0.7 dB
- IM_3 radiation with DPD is suppressed by 3.3 dB

Thank you