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WSJ-5

MISO Load Modulated Power Amplifiers with Digital Predistortion

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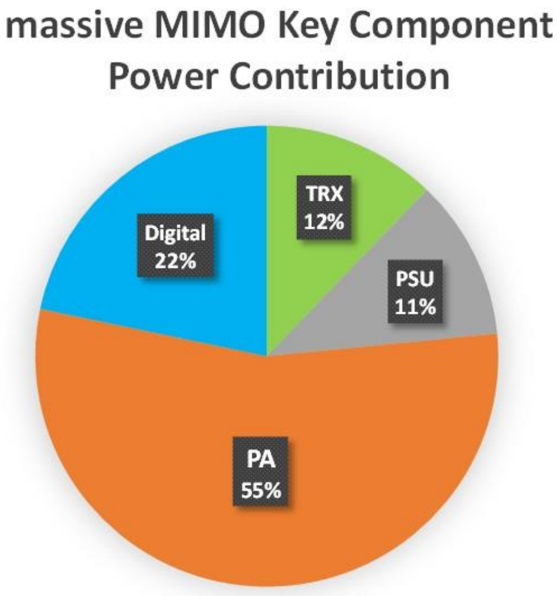
Anis Ben Arfi, William Thompson, Mark Cope

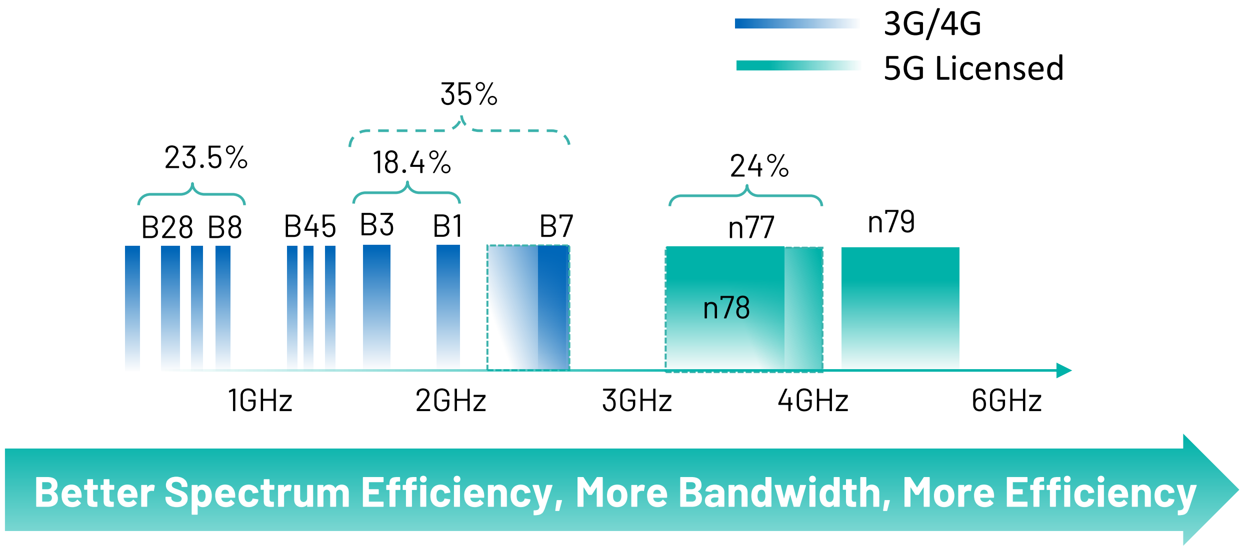
Analog Devices, Inc.,

Presentation Outline

- Introduction
- Load Modulated Power Amplifiers
- Doherty Amplifier (DPA)
  - MISO Doherty
  - Shaping Function
- Load Modulated Balanced Amplifier (LMBA)
- Pseudo-Doherty LMBA (PD-LMBA)
  - MISO Pseudo-Doherty LMBA
  - Shaping Function
- Digital Predistortion (DPD)
  - MISO Doherty with DPD
  - MISO PD-LMBA with DPD
- Conclusions
- Next Steps

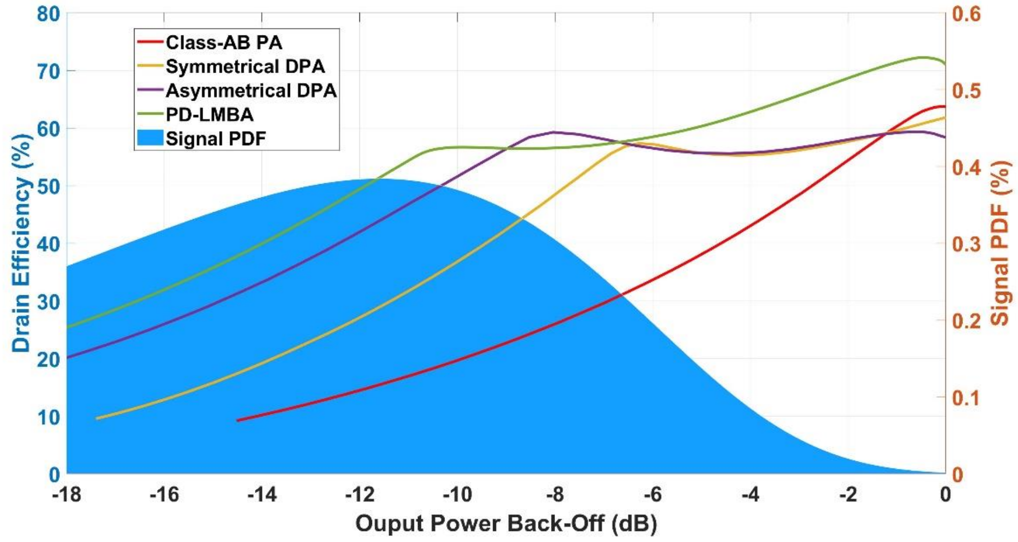
Introduction





- Typical DC Power Consumption
  - 64Tx Transmit Power: 160 EAC; 2W/TX
  - 3.16W/PA – PA Eff. =40% (1.5dB PA post loss/TX)

Radio Component	DC Power [W]
Transceiver (64TX/64RX)	112
64x PA (Eff= 40% each)	506
Digital (FPGA)	200
PSU	104
Total DC Power [W]	922



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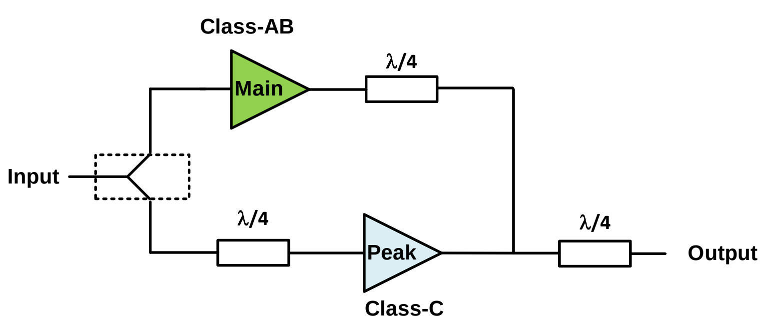
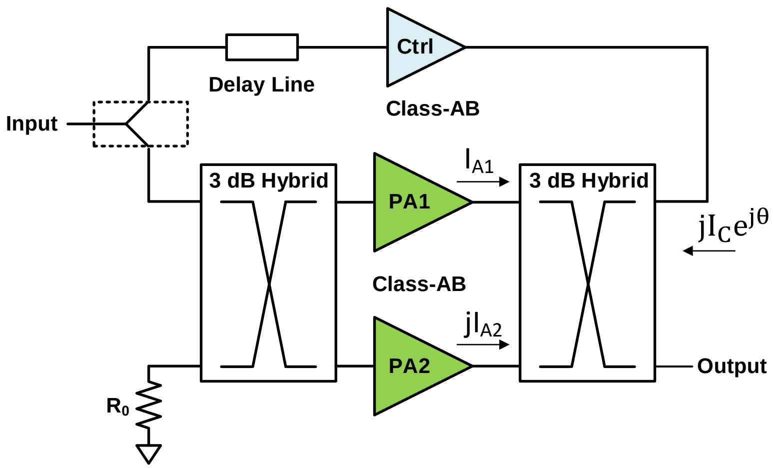
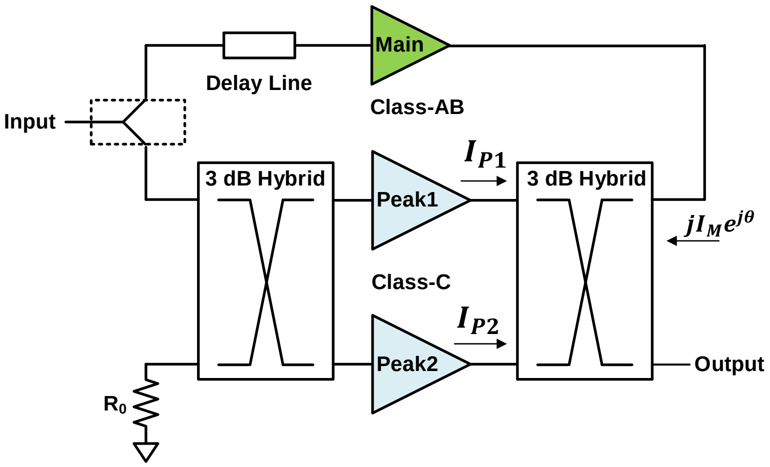
Load Modulated Power Amplifiers







- Highly Efficient
- Narrow-band (~25%)
- Relatively easy to linearize
- Mainstream PA since 3G era

- Medium Efficiency
- Broadband (~50%)
- Relatively easy to linearize
- R&D Stage

- Highly Efficient
- Broadband (~50%)
- Hard to linearize
- R&D Stage

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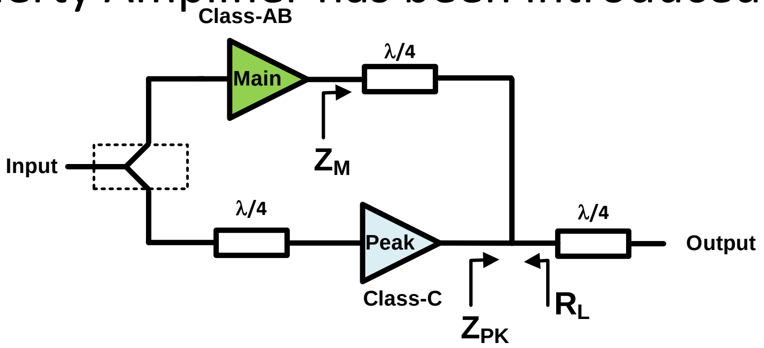
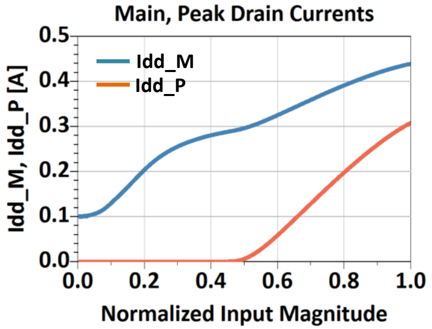
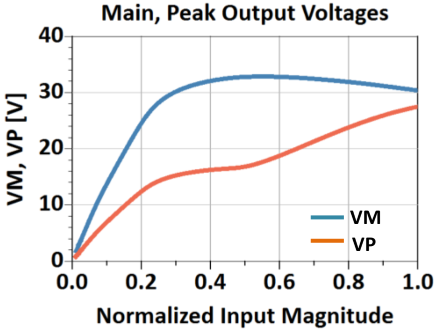
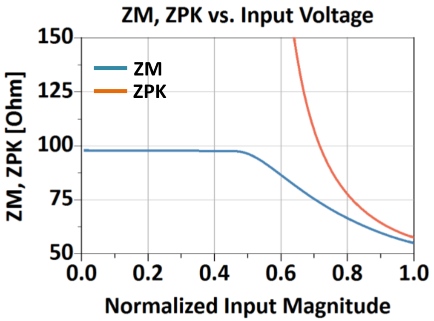
Doherty Amplifier

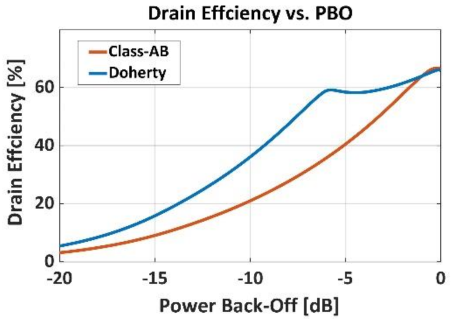
- The Doherty Amplifier has been introduced by William H. Doherty at Bell Labs in 1936 [1]



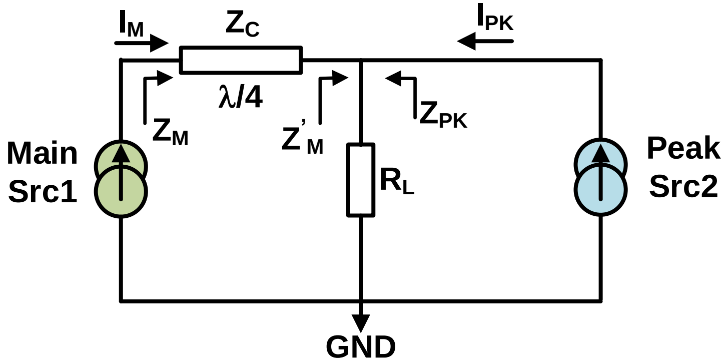








- Doherty Design Equations:



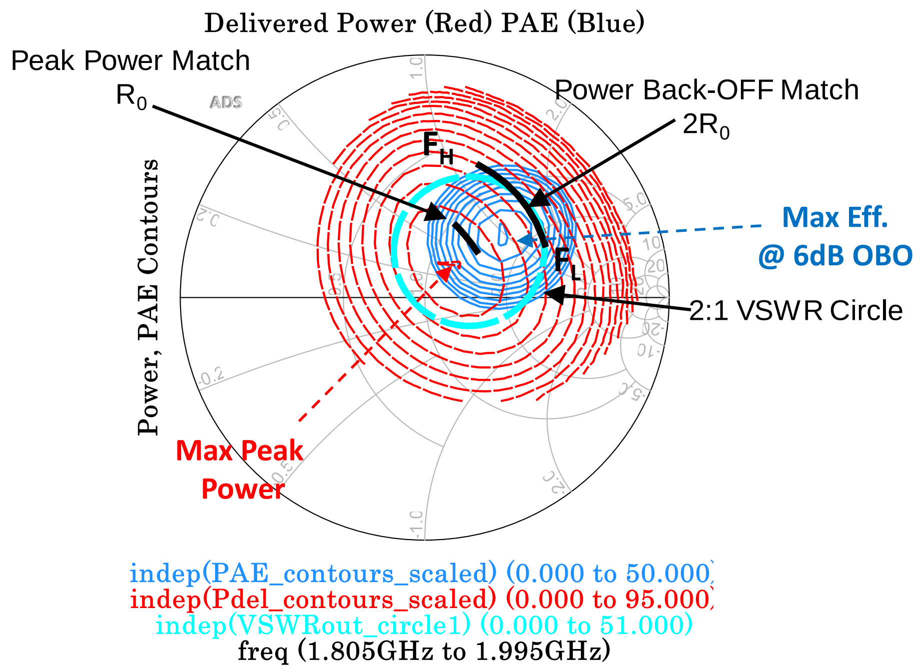
- $R_L = {}^{R_0}/_{2}\ , Z'_M = R_L\left(1+\frac{I_{PK}}{I_M}\right), Z_C = \sqrt{Z_M \times Z'_M} = \frac{R_L}{\alpha}$
- α: main to total power ratio at peak power
- $Z_M = \frac{R_L}{\alpha^2\left(1+\frac{I_{PK}}{I_M}\right)}$ and $Z_p = R_L\left(1+\frac{I_M}{I_{PK}}\right)$
- 2 regimes:
  - Power back-off regime: $I_{PK} = 0\ A, Z_M = \frac{R_L}{\alpha^2}$ and $Z_{PK}=\infty$
  - Peak Power regime: $I_M = I_{PK}, Z_M = Z_{PK} = \frac{R_L}{2\alpha^2}$

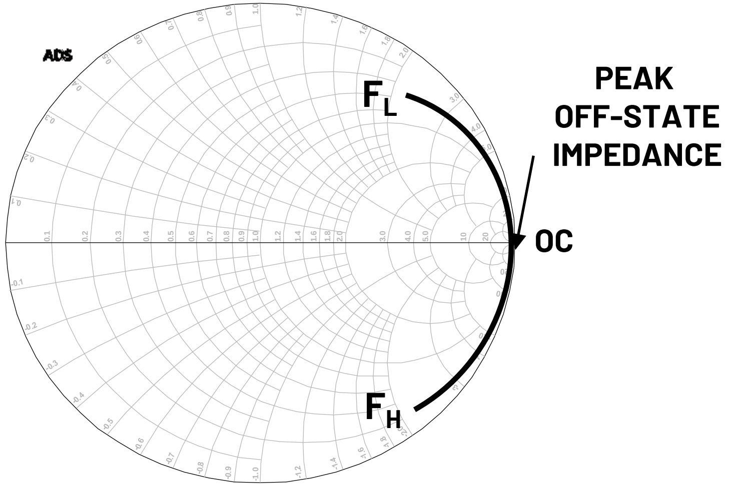
[1] W. H. DOHERTY, "A NEW HIGH EFFICIENCY POWER AMPLIFIER FOR MODULATED WAVES, Proceedings of the IRE, Vol. 24, Number 9, Sept. 1936

Doherty BW Limitations

- Doherty PA is inherently narrow-band !
  - High Q power device impedances
  - Doherty combiner BW
  - Matching Network dispersion
  - Efficiency contours vs frequency
  - Doherty Power dependent phase unbalance

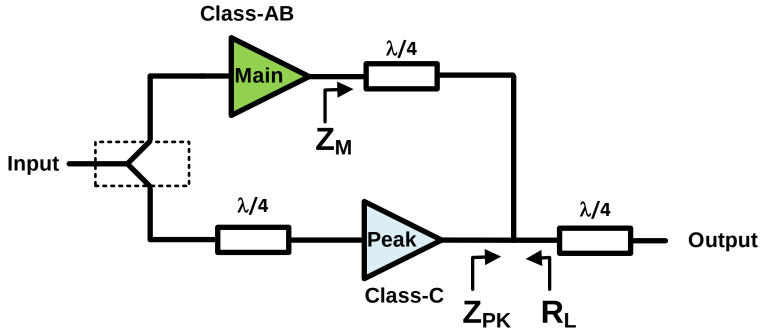
Frequency [MHz]	Dev1 Z Load [Ohm]	Dev2 Z Load [Ohm]
1805	11.8+j13.2	11.8 +j1.2
1880	9.2+j12.5	9.2+j0.5
1995	6.0+j12.9	6.0+j0.9
2200	7.5-j14.5	7.5-j2.5
	X	√





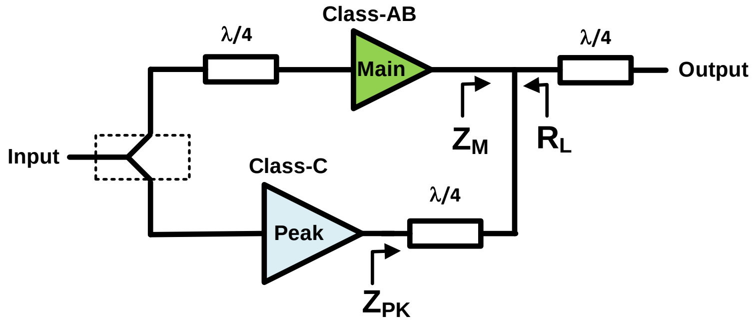
Doherty Variants

Symmetrical DPA

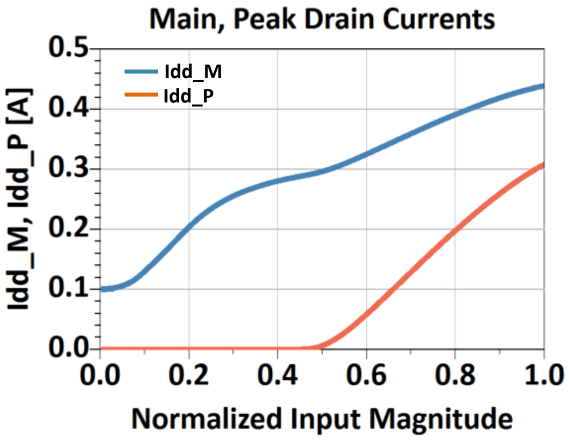


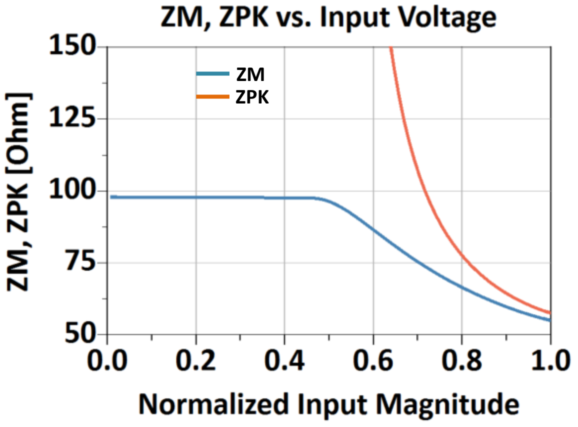
- Symmetrical Doherty:
  - α = 0.5, R_L = 25 Ohm
  - Z_{MOD} = 100 Ohm, Z_{OPT} = 50 Ohm
  - Full load modulation not possible

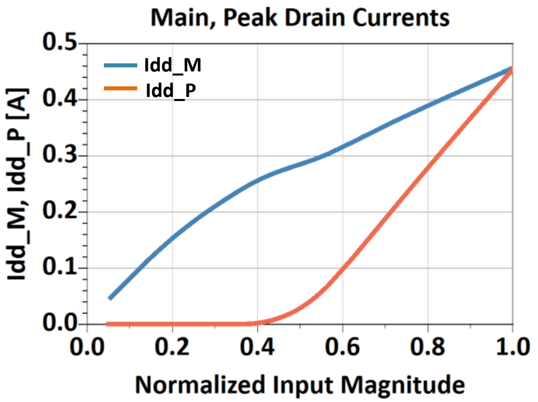
Asymmetrical Inverted DPA

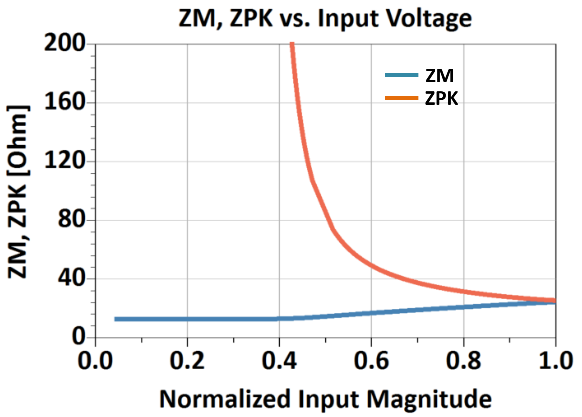


- Asymmetrical Inverted Doherty:
  - α = 0.4, R_L = 12.5 Ohm
  - Z_{MOD}=12.5 Ohm, Z_{OPT}=31.25 Ohm
  - Full load modulation



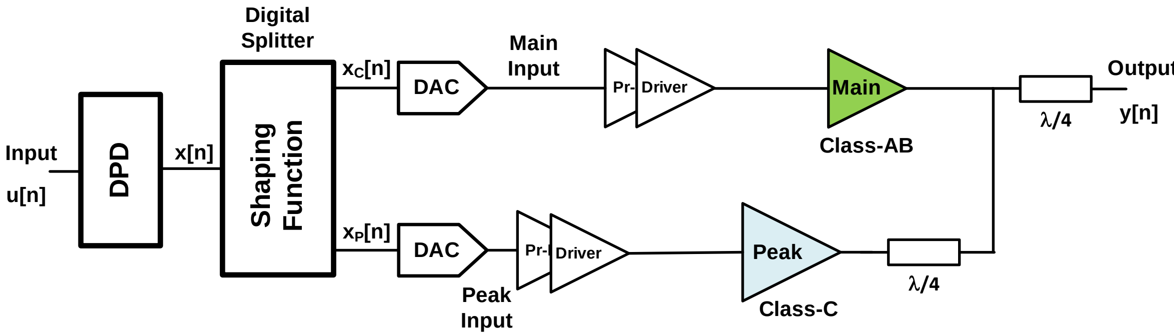






MISO Doherty PA

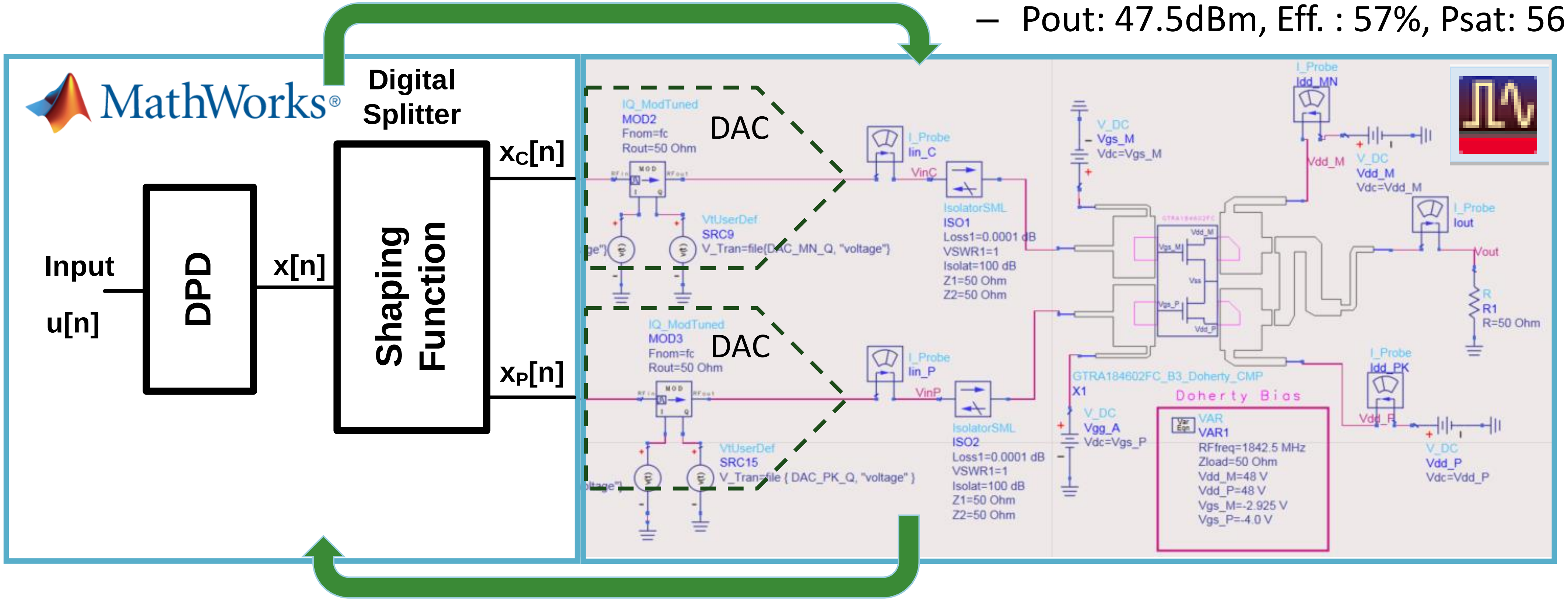
- Carrier and Peak input split
  - Better control of the input drive levels
  - Maximize the Doherty efficiency
  - Improve the linearity
  - Improve the Doherty bandwidth



- Digital Splitter
  - Optimized Carrier $x_C[n]$ and Peak $x_P[n]$ Shaping Function magnitude and phase
  - Multiple Shaping Function solutions
    - Mag & Phase opt vs. power; Eff.
    - Phase opt vs. frequency; BW
  - Single input Digital Predistortion (DPD)

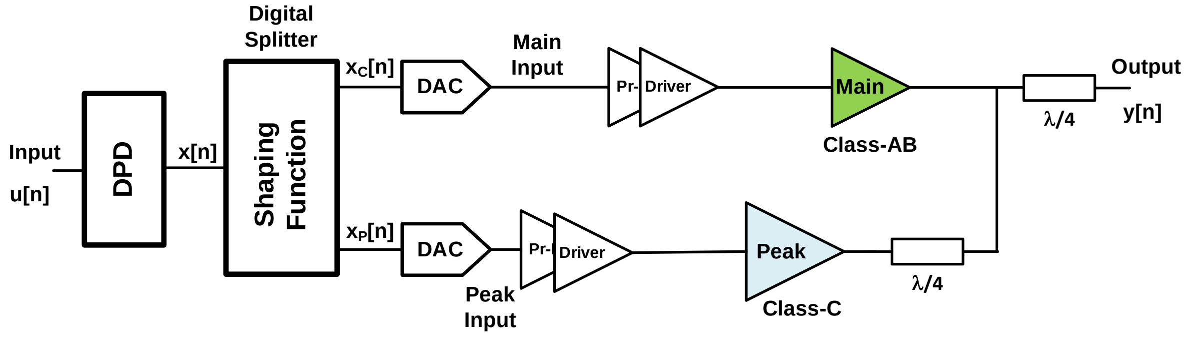
MISO Doherty Co-Simulation

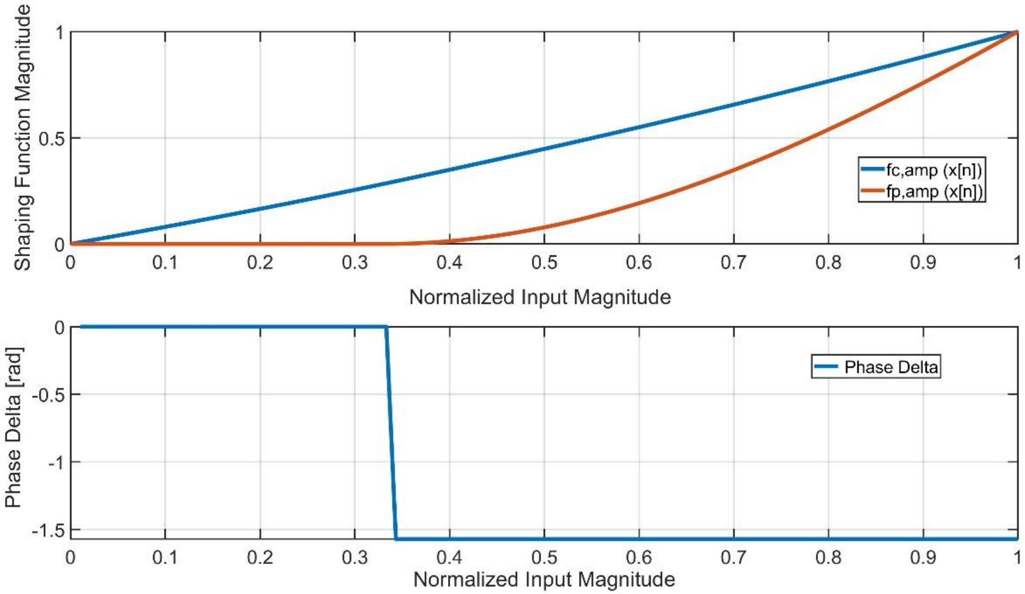
- MISO Doherty MATLAB-ADS Co-simulation
  - Shaping function extraction
  - Digital Predistortion (DPD)
- **ADI B3 40W Inverted Doherty Sim.**
  - GTRA184602FC, 460W (P3dB)
  - Operating frequency: 1805-1880 MHz
  - Pout: 47.5dBm, Eff. : 57%, Psat: 56.5dBm



Shaping Function

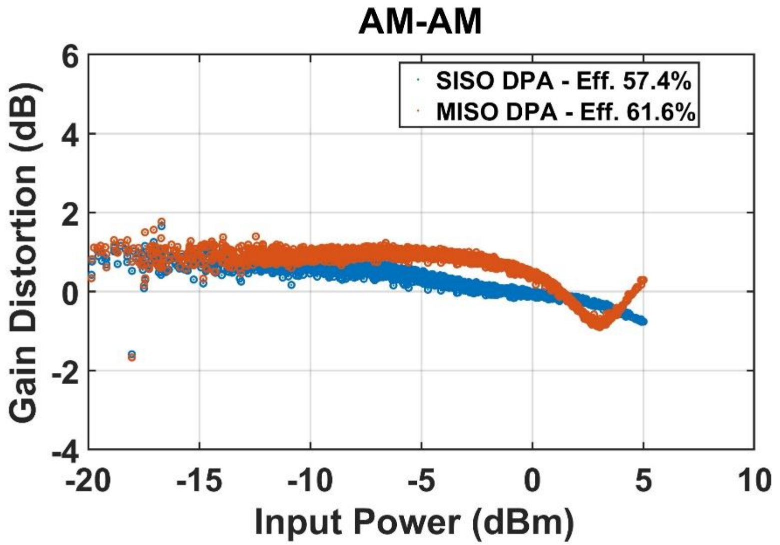
- Shaping Function extraction: 20MHz LTE (8dB PAR)

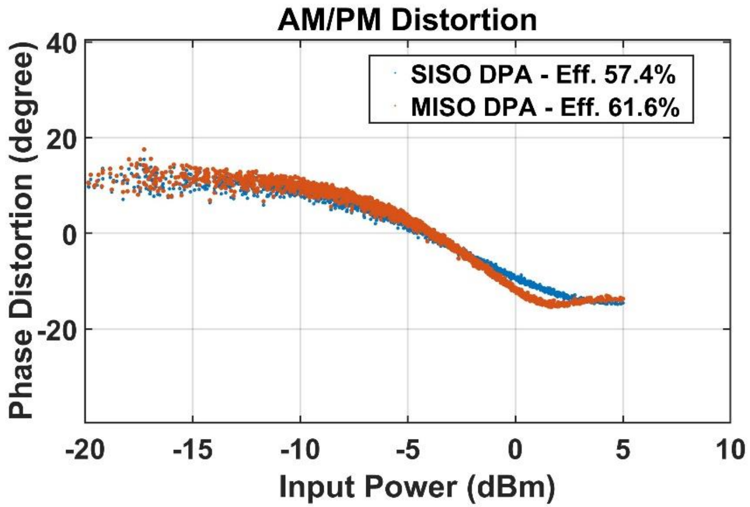




- Shaping Function Equations:

$$x_C[n] = f_{C,amp}(x[n])\, e^{i(\angle x[n] + f_{C,ph}(x[n]))}$$
$$x_P(n) = f_{P,amp}(x[n])\, e^{i\angle x[n]}$$





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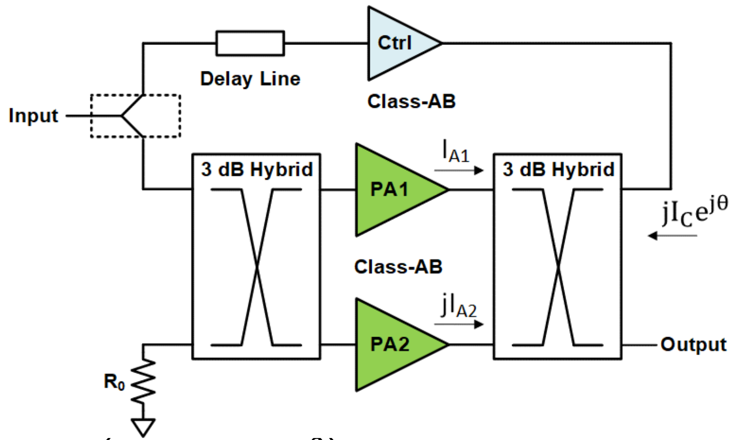
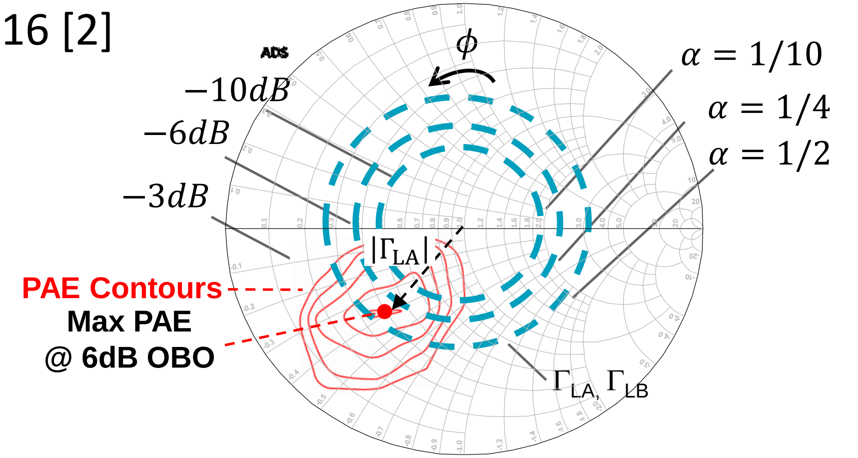
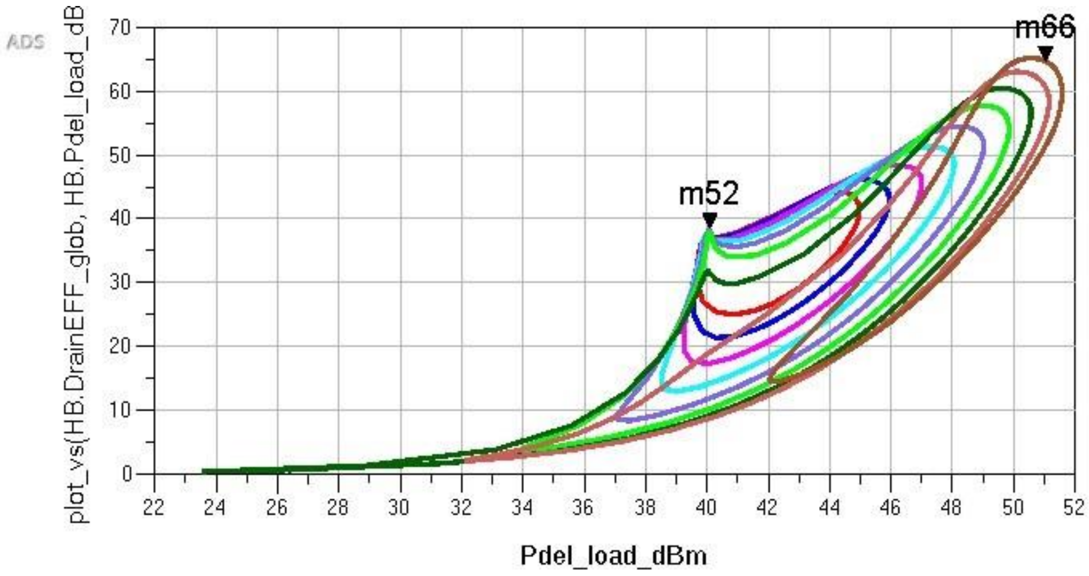
Load Modulation Balanced Amplifier (LMBA)

- The LMBA has been introduced by D. J. Shepphard and S. Cripps in 2016 [2]



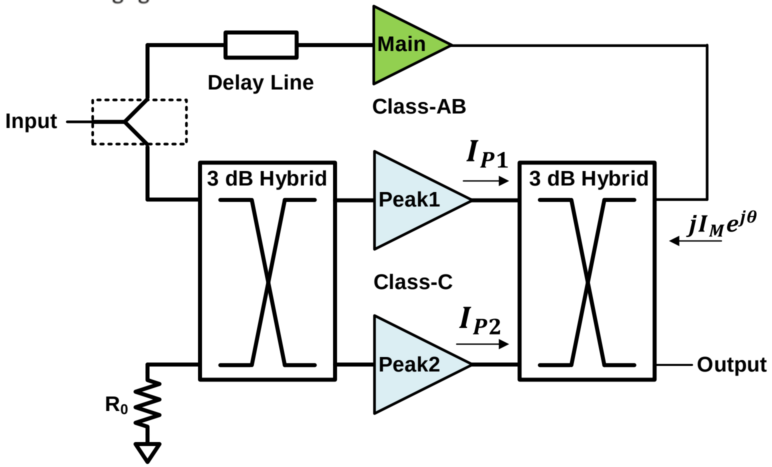


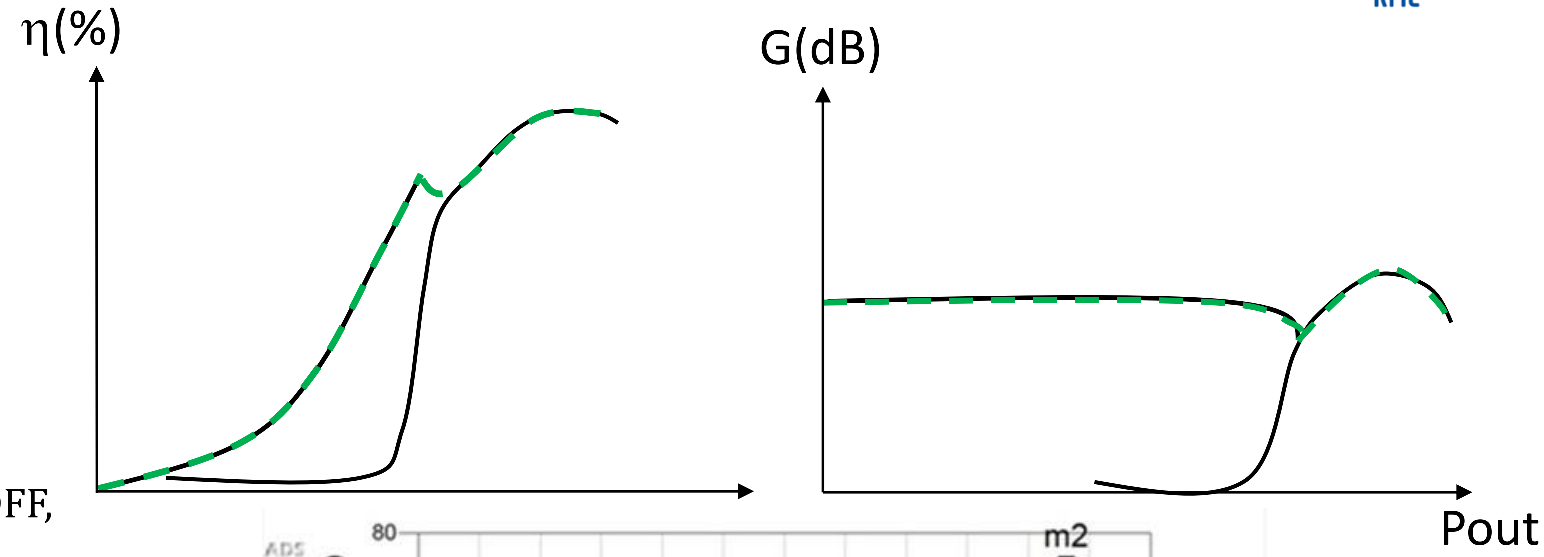
- $Z_{A1} = Z_{A2} = \left(1 + \sqrt{2}\frac{I_C e^{j\emptyset}}{I_A}\right); I_{A1} = I_{A2} = I_A$ (1)
- I_C, I_A: main to total power ratio at peak power
- $P_A = P_{A1} = P_{A2} = \frac{1}{2} I_A^2 Z_0 Re\left\{1 - \sqrt{2}\frac{I_C e^{j\emptyset}}{I_A}\right\} = Z_0\left(I_A^2 - \sqrt{2} I_A I_C \cos\emptyset\right)$ (2)
- With $P_{cont} = \frac{1}{2} I_C^2 Z_c$ and with $Z_c = Z_0$ (3)
- $P_{out} = Z_0\left(I_A^2 - \sqrt{2} I_A I_C \cos\emptyset + \frac{1}{2} I_C^2\right) = 2\times P_A + P_{cont}$ (4)
- With $\alpha = \left|\frac{P_{cont}}{P_A}\right|$ sets the mod. impedances for Z_{A1} and Z_{A2}
- $\emptyset = \angle \frac{P_{cont}}{P_A}$: sets the rotation angle on the constant amplitude

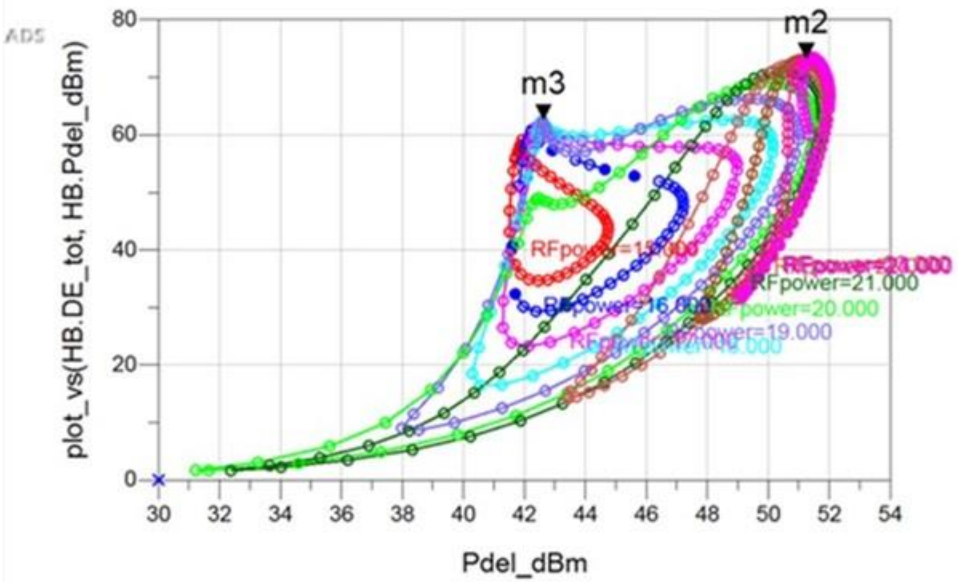


[2] D.J. Sheppard, J. Powell, and S C. Cripps, "An Efficient Broadband Reconfigurable Power Amplifier Using Active Load Modulation", IEEE Microwave & Wireless Components Letters, Vol. 26, No. 6, June 2016

Pseudo-Doherty LMBA (PD-LMBA)







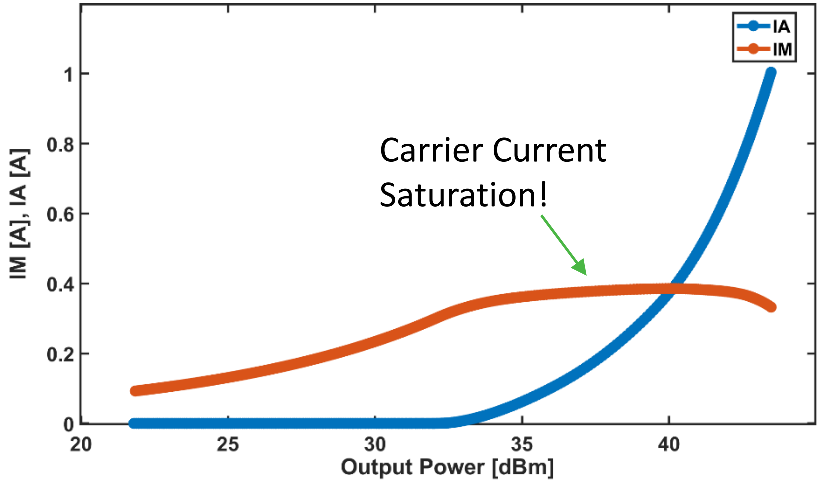
- Low power regime: up to PBO, Peak1, Peak2 OFF,
  - $I_{P1} = I_{P2} = 0$ A
- $Z_{P1,PBO} = Z_{P2,PBO} = Z_0\left(1 + \sqrt{2}\frac{I_M e^{j\emptyset}}{I_{P1,P2}}\right)$
- $Z_{P1,PBO} = Z_{P2,PBO} = \infty$
- $Z_{M,PBO} = Z_0$

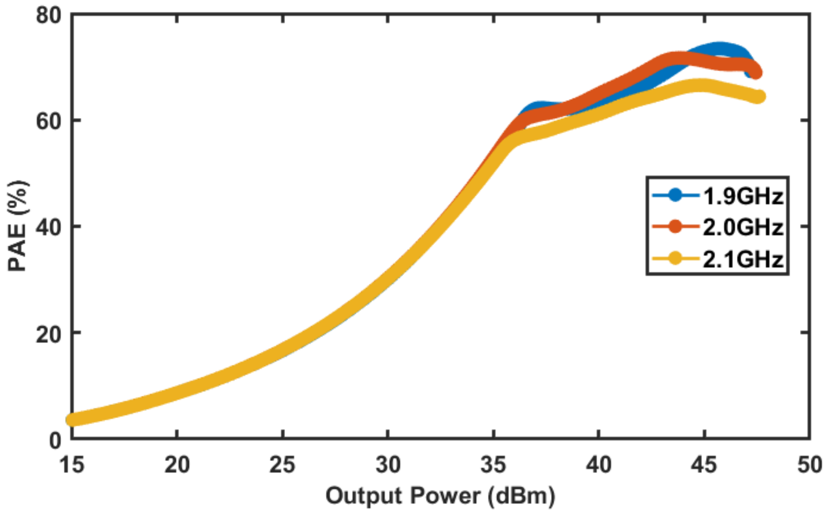
- High power regime: PBO to P_{SAT} ,
  - $I_M = I_{M,Max}$, $I_{P1} = I_{P2} = I_{P,Max}$
- $Z_{P1,SAT} = Z_{P2,SAT} = Z_0\left(1 + \sqrt{2}\frac{I_{M,Max} e^{j\emptyset}}{I_{P,Max}}\right)$
- $Z_{M,SAT} = Z_0$

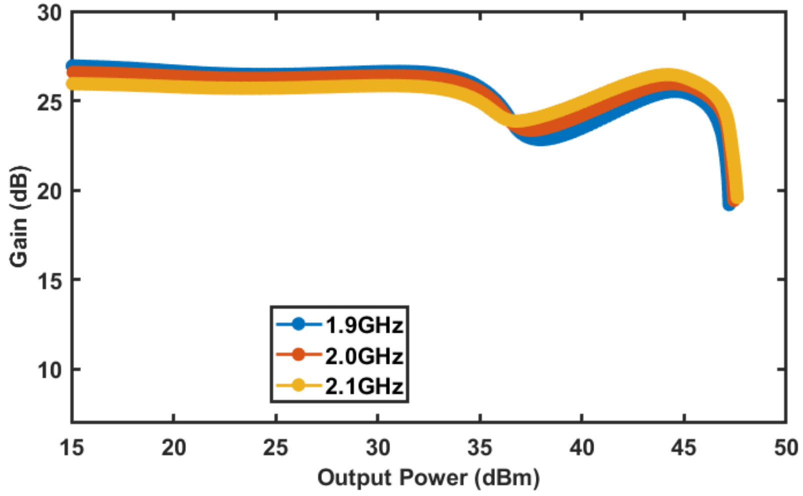
[3] Yuchen Cao and Kenle Chen, "Pseudo-Doherty Load-Modulated Balanced Amplifier with Wide Bandwidth and Extended Power Back-Off Range", IEEE Transactions on microwave theory and techniques, vol. 68, no. 7, July 2020

Pseudo-Doherty LMBA (PD-LMBA)

- Pseudo-Doherty LMBA
  - Highly efficient at 10+ dB power back-off
  - Main stage IM compresses up to Psat!
  - AM-AM hardly compressed (hard to linearize!)

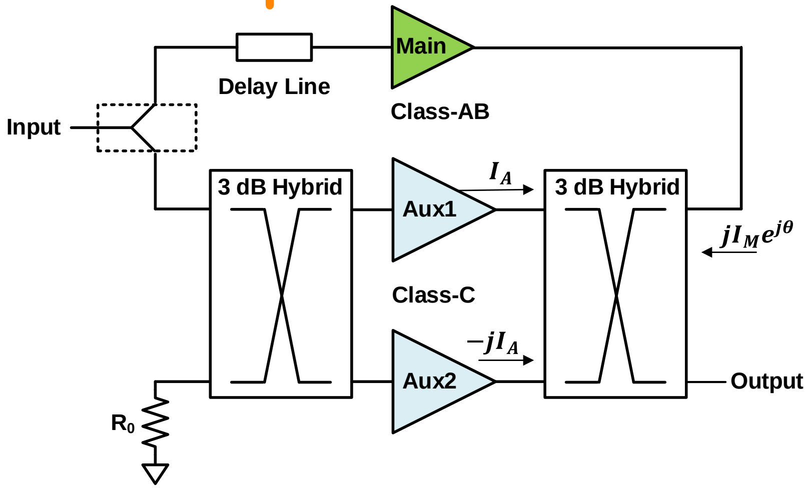


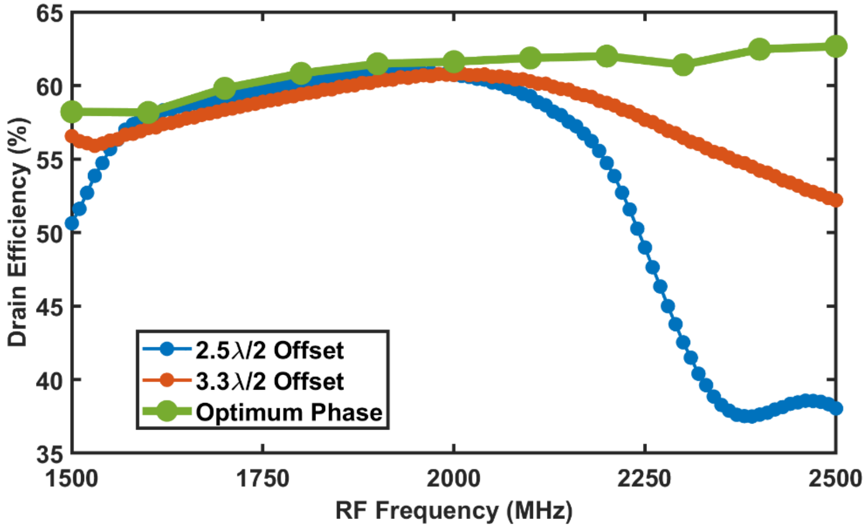


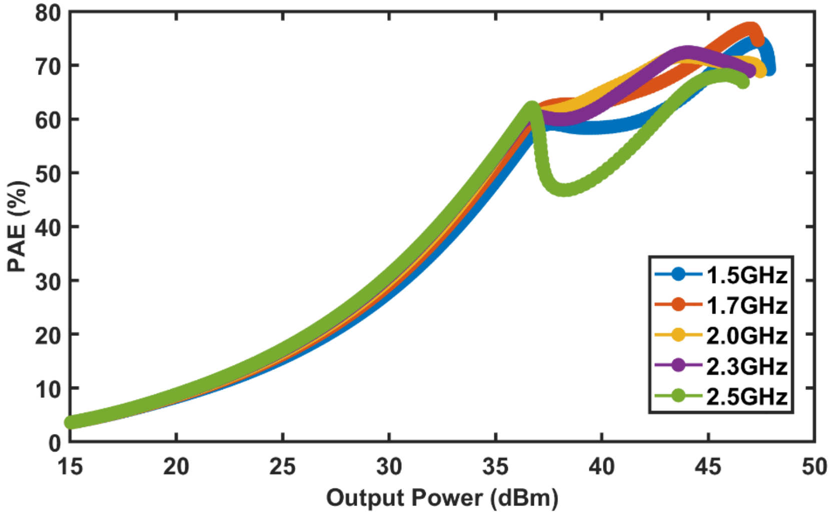


PD-LMBA Bandwidth

PA Configuration	Input Offset Line Length [cm]	Frac. BW [%]	DE [%]
SISO PD-LMBA	11.2	25	~55%
SISO PD-LMBA	14.8	40	~55%
MISO PD-LMBA	N/A	>50	~60%



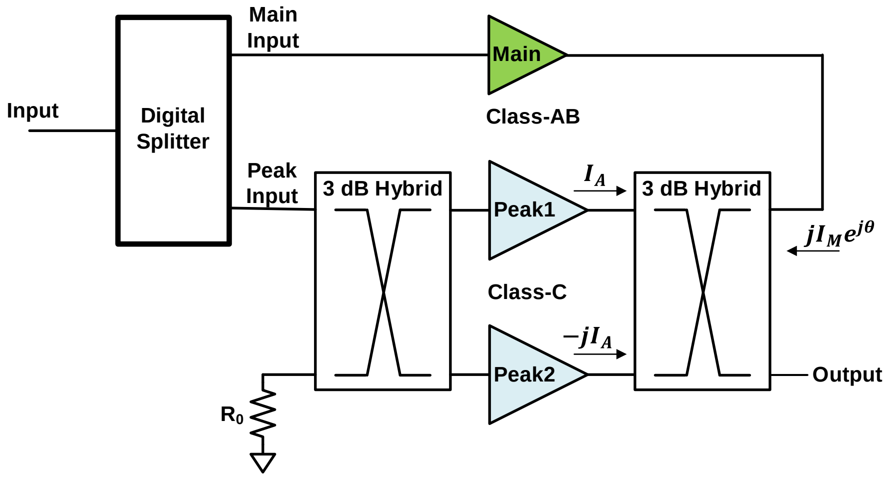




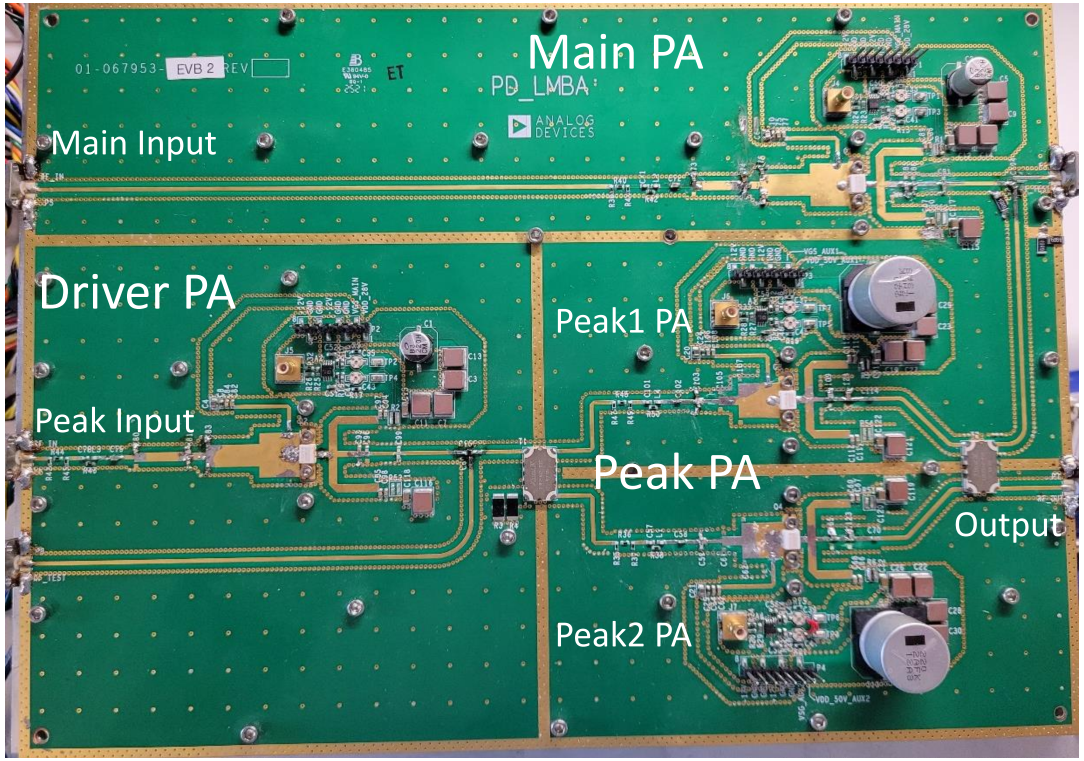
MISO PD-LMBA

- Carrier and Peak input split
  - Better control of the input drive levels
  - Maximize the PD-LMBA efficiency
  - Improve the linearity

- Digital splitter
  - Main and Peak Shaping function

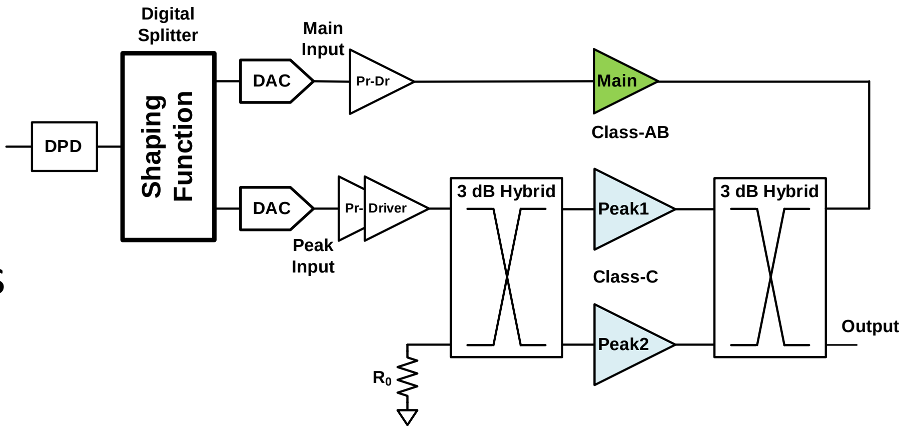


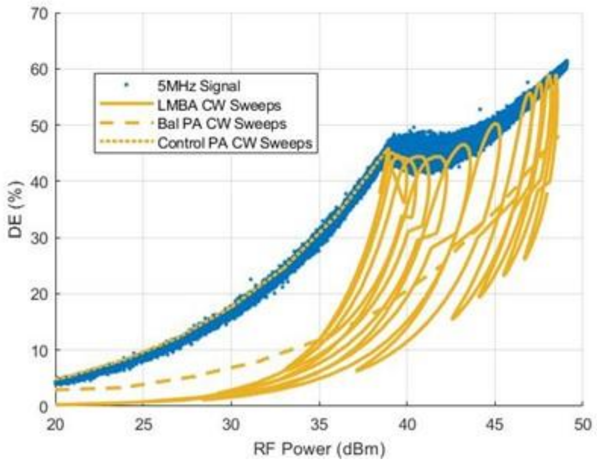
- **Analog Devices PD-LMBA prototype**:
  - Main PA: 10W CGH40010 (Class-AB)
  - Peak PA: 2x 30W CGHV40030 (Class-C)
  - Driver PA: 10W CGH40010 (Class-AB)
  - Operating frequency: 1.5-2.5GHz
  - Pout: 40dBm, Eff. : 50+%, Psat: 47.8dBm

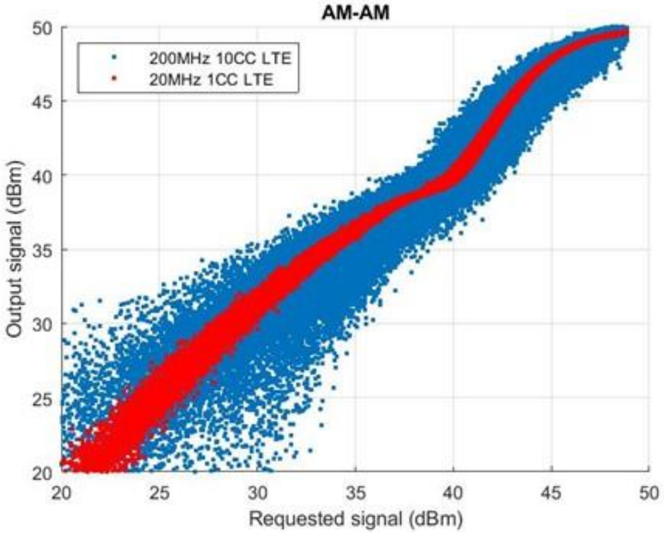


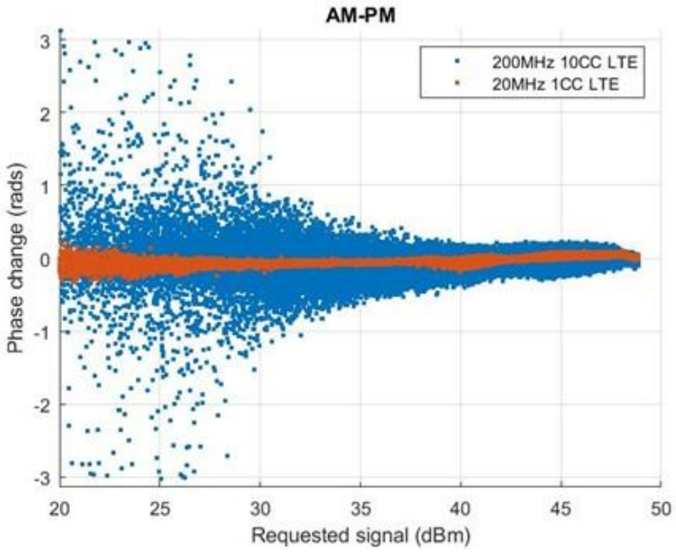
MISO PD-LMBA Shaping Function 1 (ADI)

- Digital splitter
  - Optimum dual input drive levels
    - Carrier Shaping function
    - Peak Shaping function
- Shaping Function
  - Instantaneous efficiency extraction
  - Linearity improvement

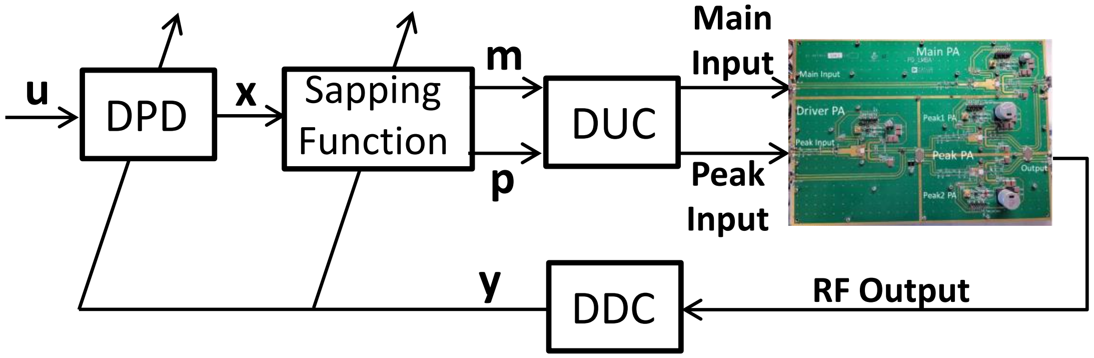








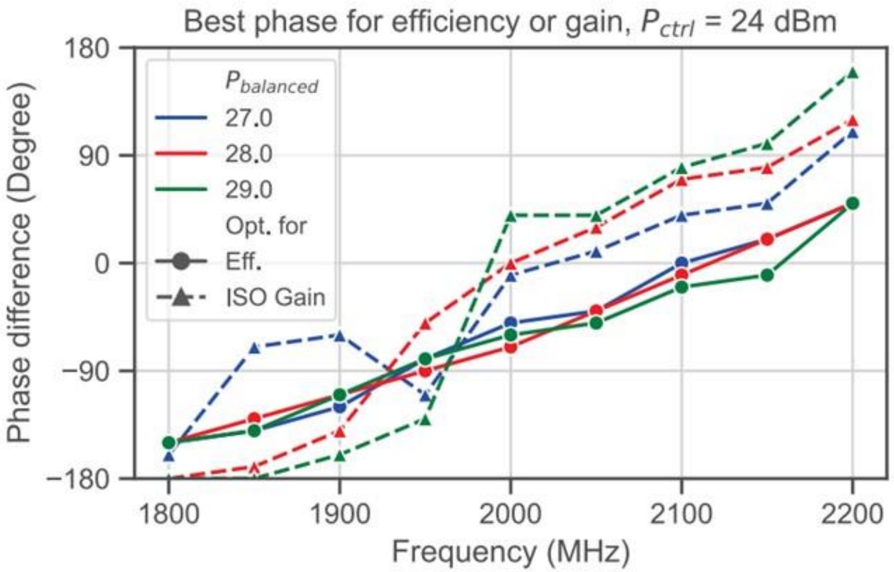
MISO PD-LMBA Shaping Function 2 [UPC]

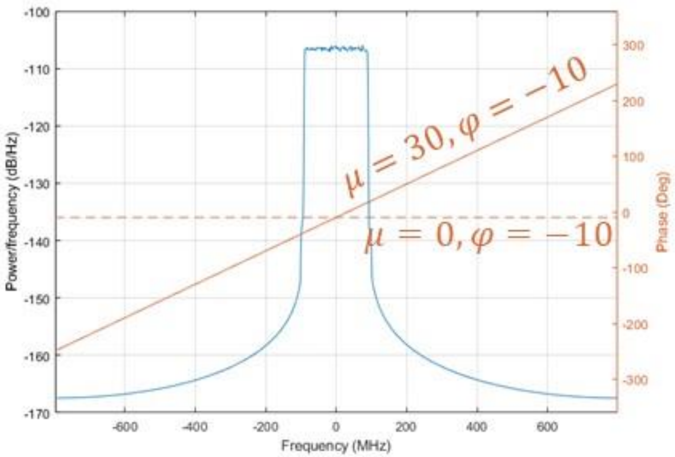


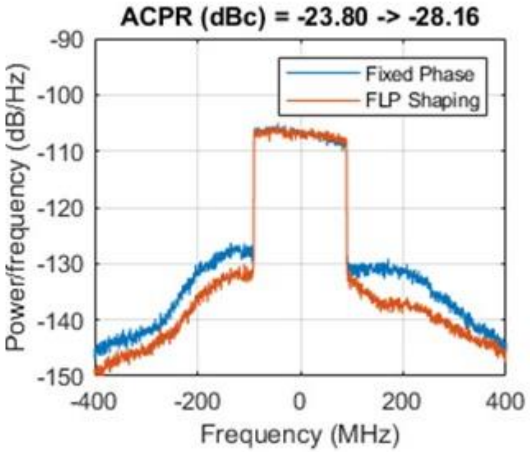
- Frequency-Domain Linear Shaping [4]

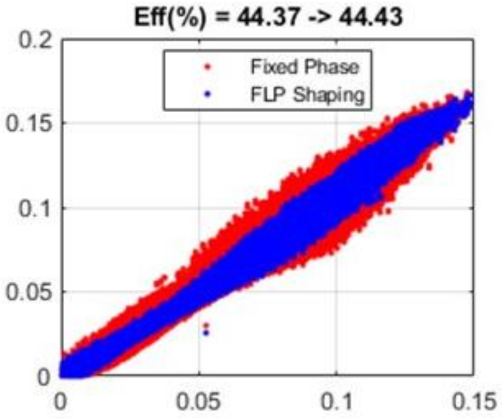
$$X[k] = DFT_N\{x[n]\}$$
$$M[k] = (1 + A[k])\, X[k]\, e^{-i\theta[k]}$$
$$P[k] = (1 - A[k])\, X[k]\, e^{+i\theta[k]}$$

$$A[k] = \begin{cases} \alpha k + \beta & (k_L \le k \le k_U) \\ \beta & (others) \end{cases}$$
$$\theta[k] = \mu k + \varphi$$
$$m[n] = IDFT_K\{M[k]\},$$
$$p[n] = IDFT_K\{P[k]\}$$









[4] Wantao Li and al. “Digital Shaping and Linearization of a Dual-Input Load-Modulated Balanced Amplifier” , 2023 International Workshop on Integrated Nonlinear Microwave and Millimetre-Wave Circuits (INMMIC)

Presentation Outline

- Introduction
- Load Modulated Power Amplifiers
- Doherty Amplifier (DPA)
  - MISO Doherty
  - Shaping Function
- Load Modulated Balanced Amplifier (LMBA)
- Pseudo-Doherty LAMBA (PD-LMBA)
  - MISO Pseudo-Doherty LMBA
  - Shaping Function
- Digital Predistortion (DPD)
  - MISO Doherty with DPD
  - MISO PD-LMBA with DPD
- Conclusions
- Next Steps

Digital Predistortion (DPD)

- Volterra-Based Models
  - Effective behavioral modeling of non-linear systems
  - GMP derivative of Volterra Series [5]; reduced complexity (Linear Regression Estimation)

$$y(n) = \sum_{i=-I_{lag}}^{I_{lead}} \sum_{j=-J_{lag}}^{J_{lead}} \sum_{k=0}^{K} a_{ijk}\, x(n+i)|x(n+j)|^k$$

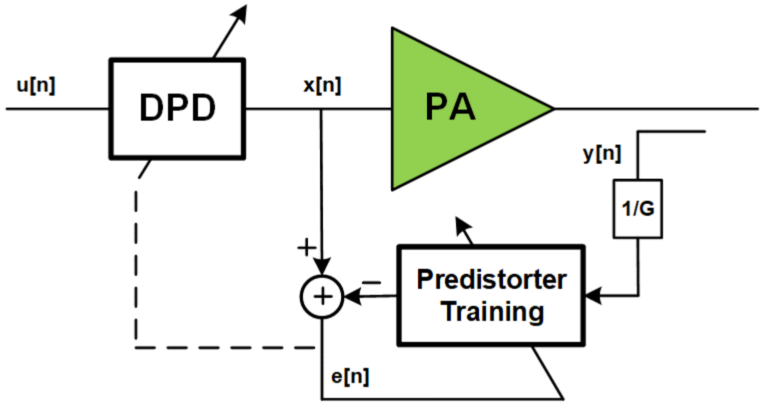
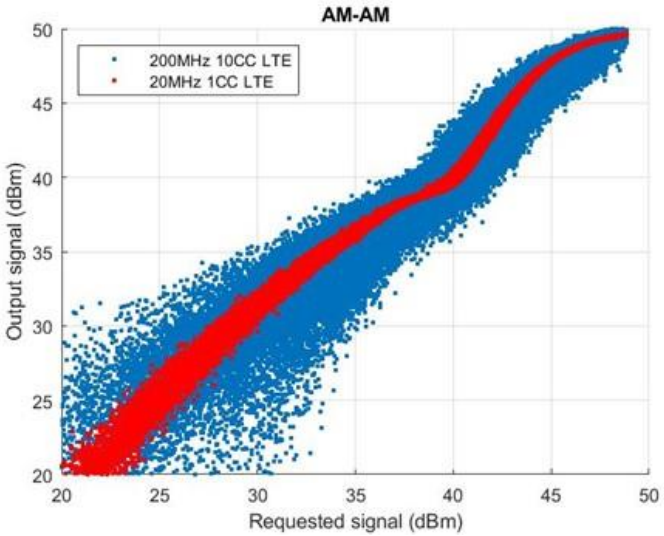


Fig. Indirect Learning

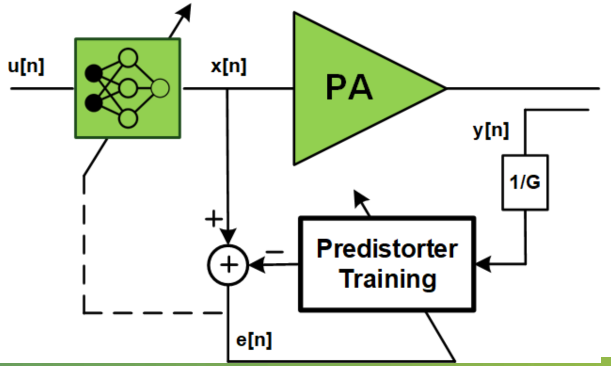
- Spline DPD [6]
  - Divides the input space in multiple regions: $[x_0, \dots, x_m]$
  - Powerful for stringent PA non-linearities

$$y(n) = \sum_{i=-I_{lag}}^{I_{lead}} \sum_{j=-J_{lag}}^{J_{lead}} x(n+i)\, S_{ij}(|x(n+j)|)$$

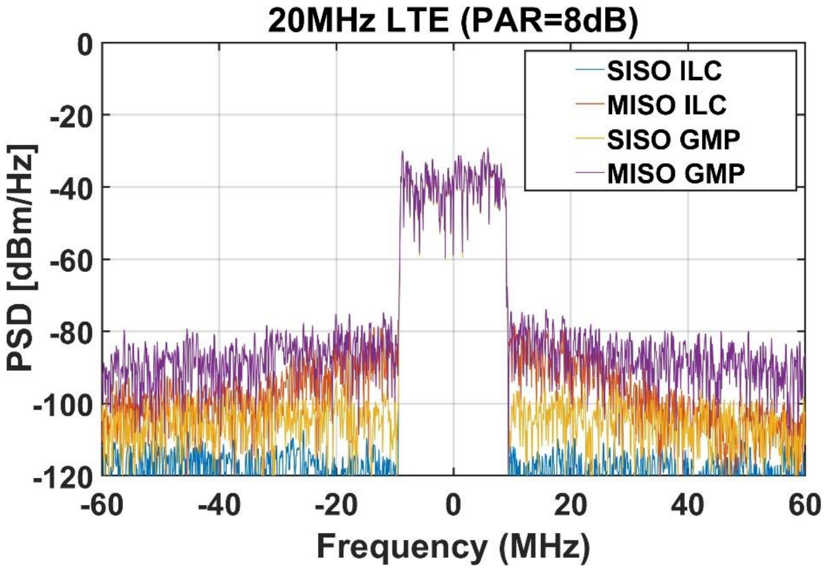
$$S_{ij}(x) = \sum_{k=0}^{3} a_{ijk,r}\,(x - x_r)^k \quad for \quad x_r \le x \le x_{r+1}$$

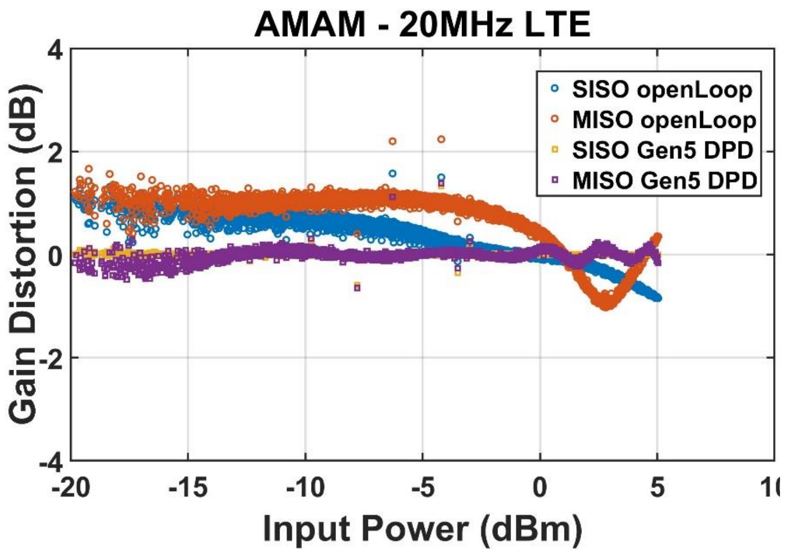


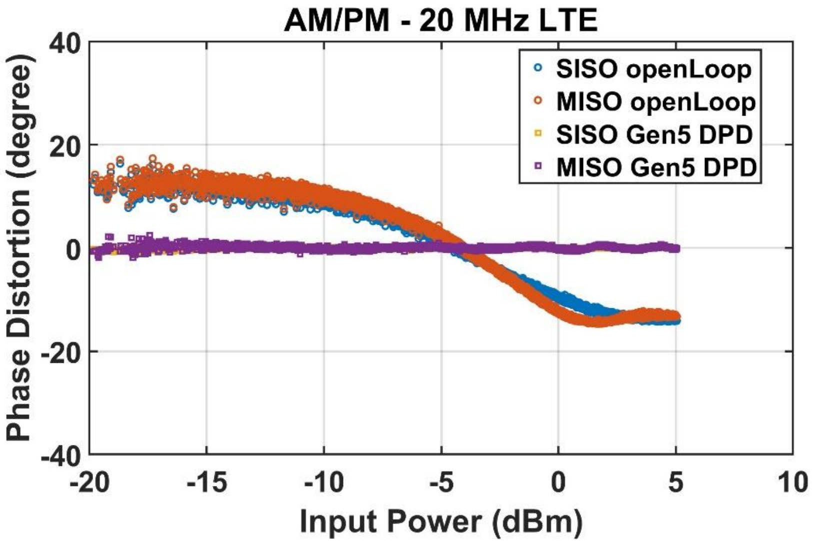
- Artificial Neural Network (ANN)
  - Captures complex non-linear mappings
  - Challenging in practical
  - Back-Propagation (Adaptation)



MISO Doherty with DPD (Co-Sim.)







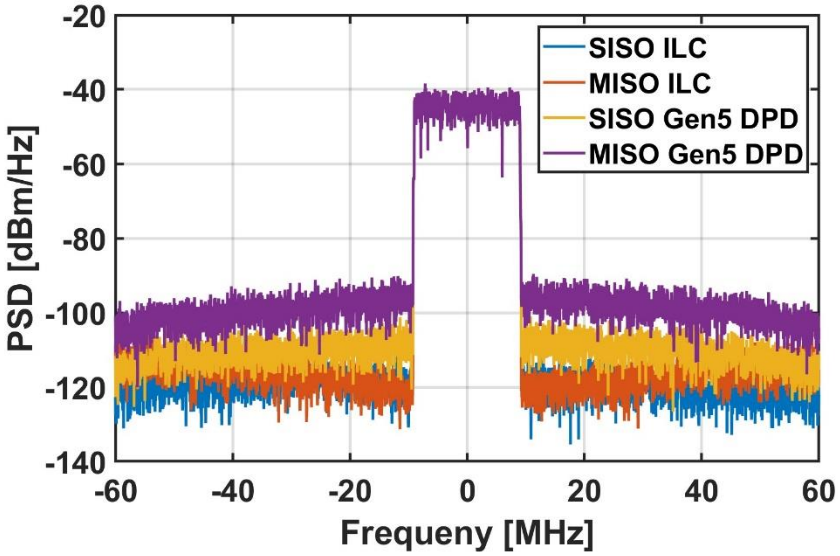
Iterative Learning Control (ILC)

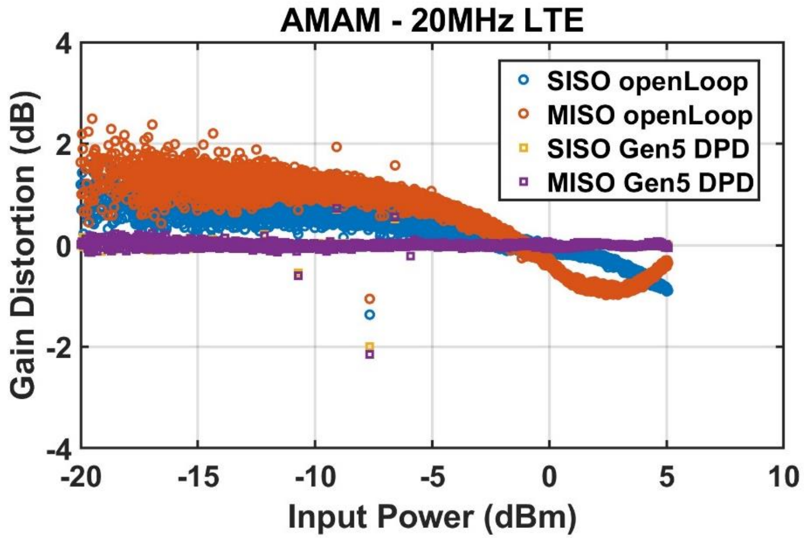
$$x_{n+1} = x_n + lr \times e_n$$
$$e_n = u_n - y_n$$

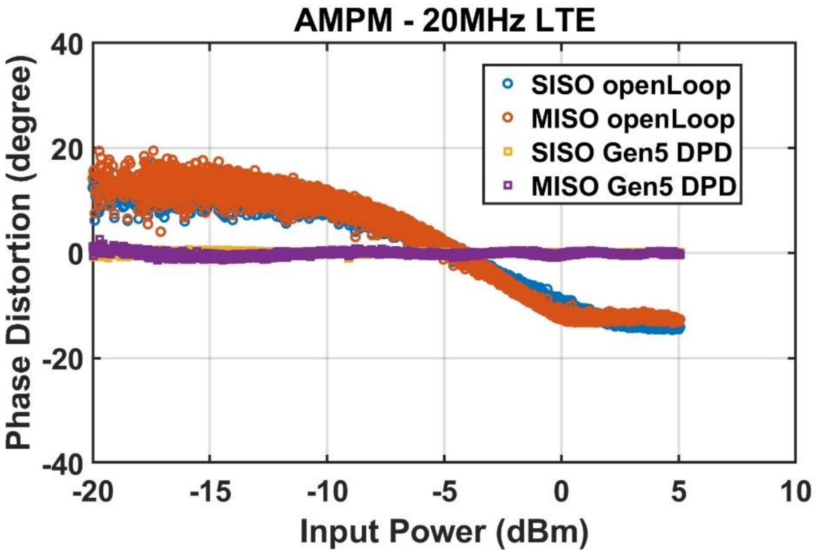
$lr: Learning\ Rate$

	NMSE [dB]	ACPR [dBc]	Pout [dBm]	Eff. [%]
SISO DPD - No DPD	-15.7	-27.4	47.7	57.4
MISO DPA - No DPD	-14.3	-24.9	47.2	61.6
SISO DPA - ILC	-48.5	-64.3	47.9	58.1
MISO DPA - ILC	-45.4	-60.9	47.4	61.6
SISO DPA - ADI Gen5 DPD	-47.7	-60.9	47.9	58.1
MISO DPA - ADI Gen5 DPD	-41.1	-50	47.8	61.7

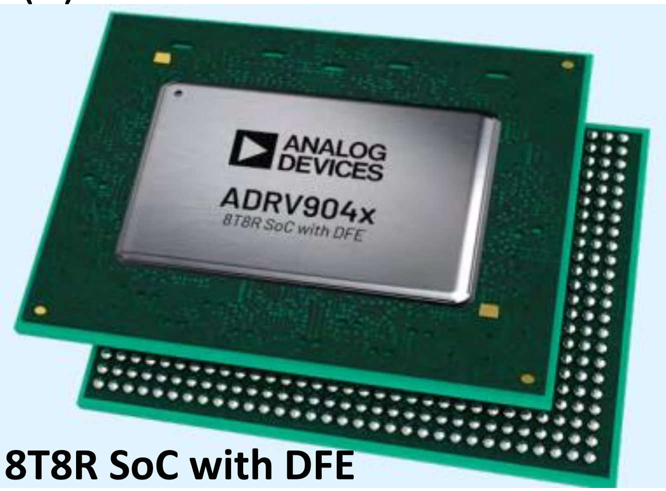
MISO Doherty with DPD (Co-Sim.)







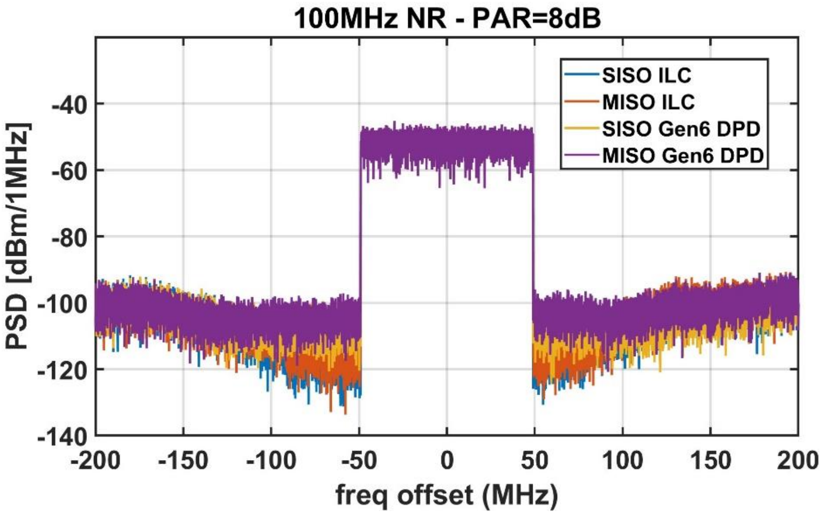
(*) Gen5 DPD in ADRV904x

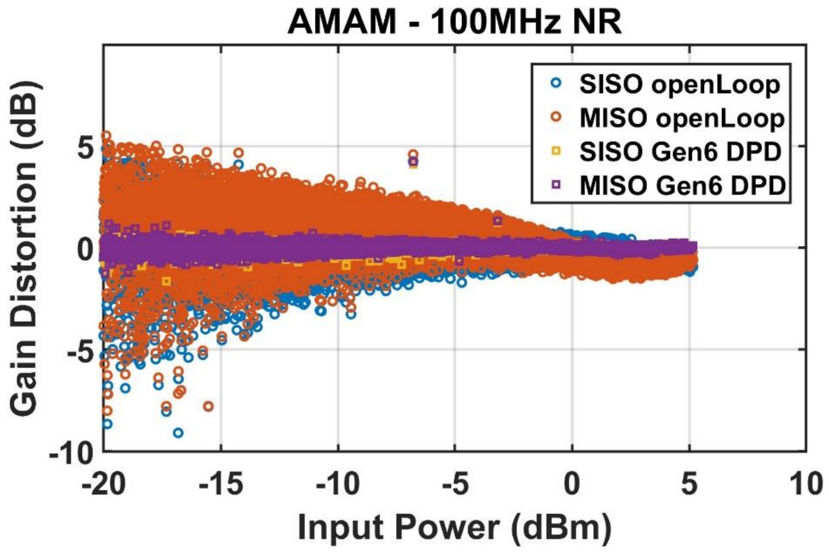


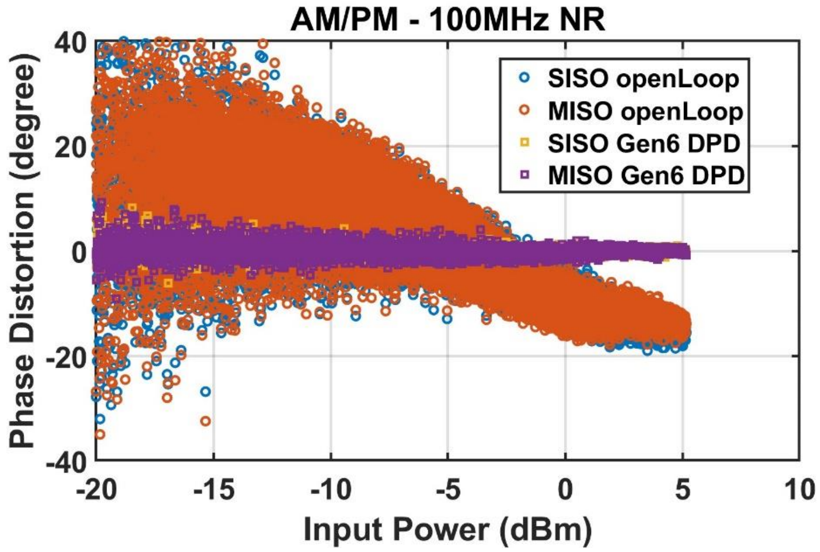
8T8R SoC with DFE

	NMSE [dB]	ACPR [dBc]	Pout [dBm]	Eff. [%]
SISO DPD - No DPD	-15.7	-27.5	47.5	57.4
MISO DPA - No DPD	-14.8	-25.6	47.5	61.6
SISO DPA - ILC	-55.6	-67.4	47.6	57.4
SISO DPA - ADI Gen5(*) DPD	-51.8	-63.0	47.7	57.4
MISO DPA - ILC	-53.3	-67.7	47.8	61.4
MISO DPA - ADI Gen5(*) DPD	-44.6	-51.9	47.8	61.4

MISO Doherty with DPD (Co-Sim.)



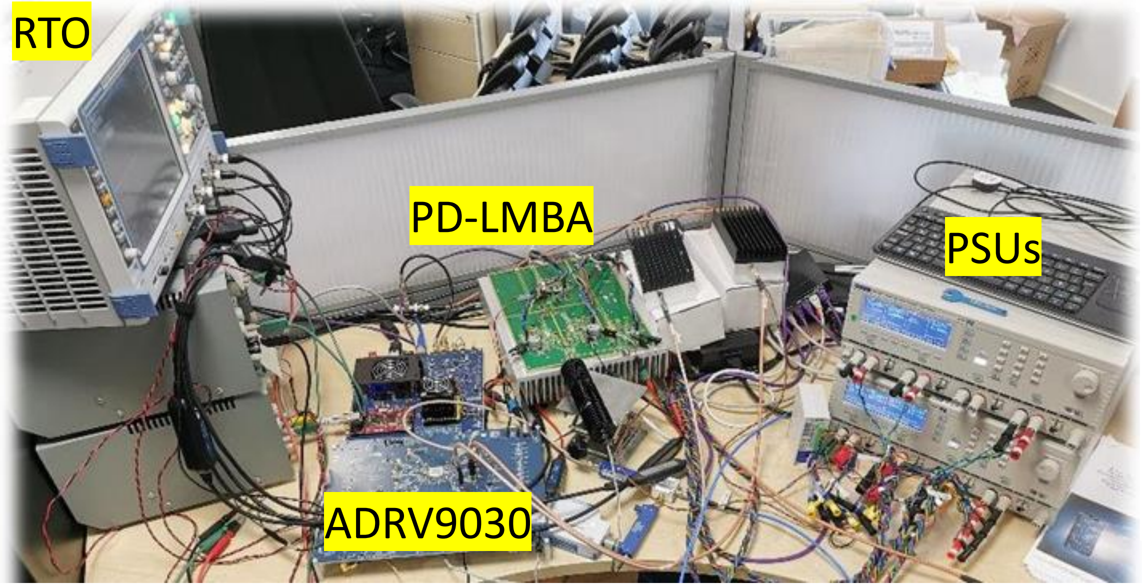


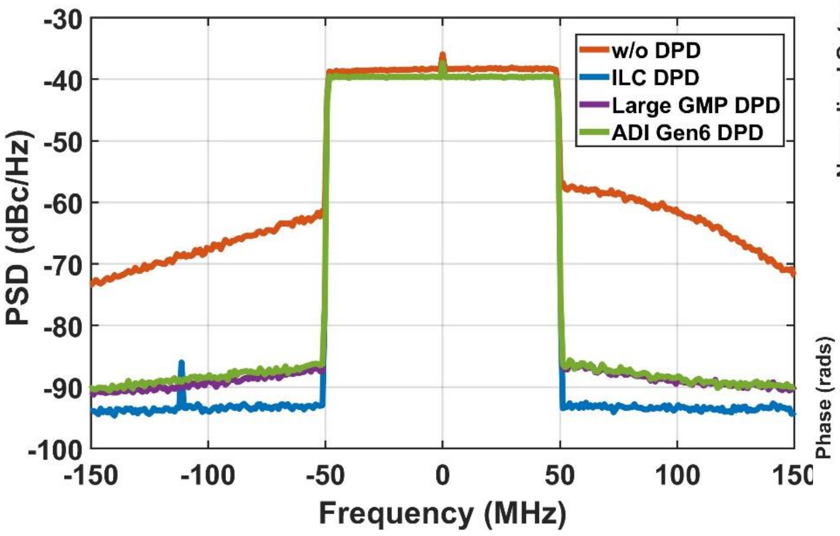


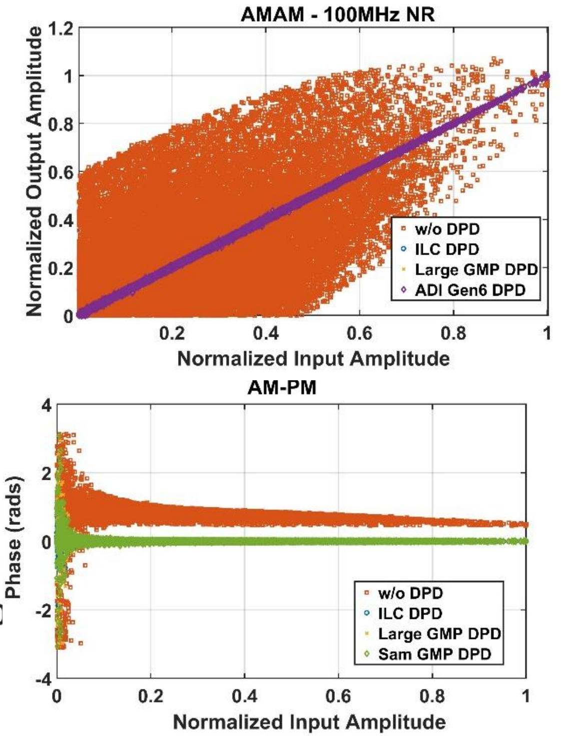
	NMSE [dB]	ACPR [dBc]	Pout [dBm]	Eff. [%]
SISO DPD - No DPD	-15.4	-26.8	47.6	54.3
MISO DPA - No DPD	-14.7	-25.3	47.5	58.7
SISO DPA - ILC	-44.0	-54.7	47.6	54.4
SISO DPA - **ADI Gen6** DPD	-43.7	-53.5	47.6	53.4
MISO DPA - ILC	-42.8	-51.6	46.6	57.4
MISO DPA - **ADI Gen6** DPD	-41.7	-50.0	47.6	57.4

Experimental Results [ADI]

- DPD Results: 100MHz NR with 8dB PAR





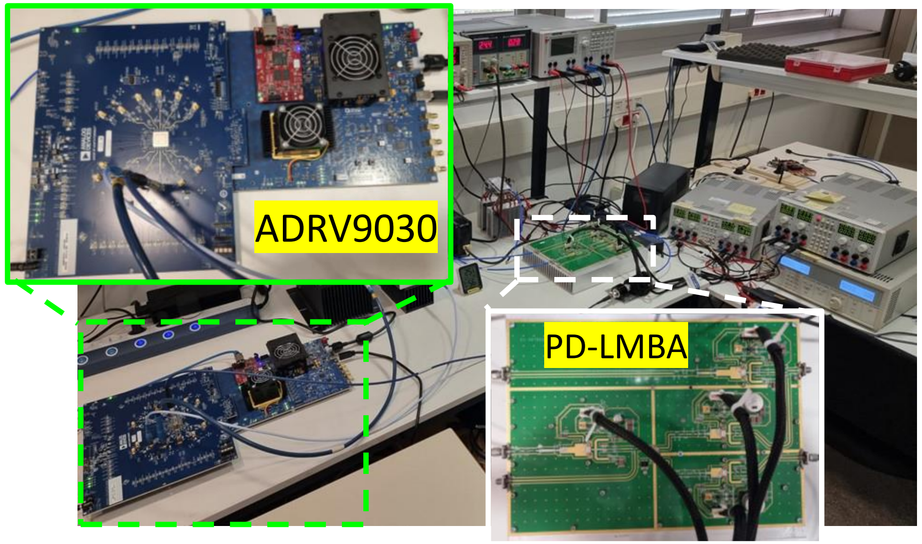


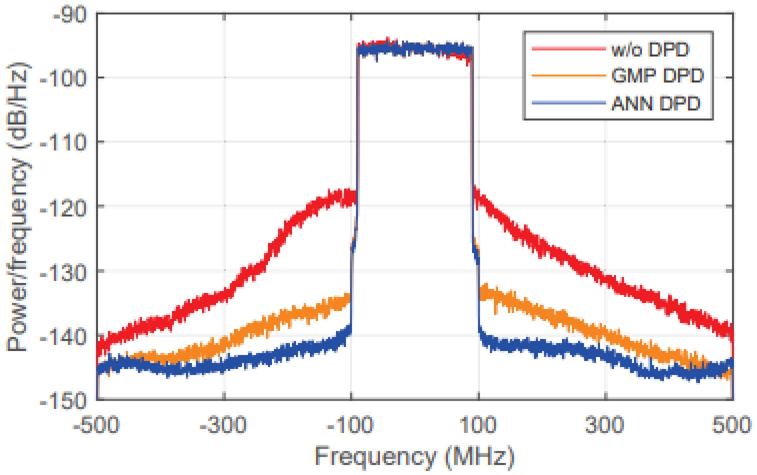
- ADI ADRV9030
  - 8T8R Transceiver
  - 600MHz-7.2GHz

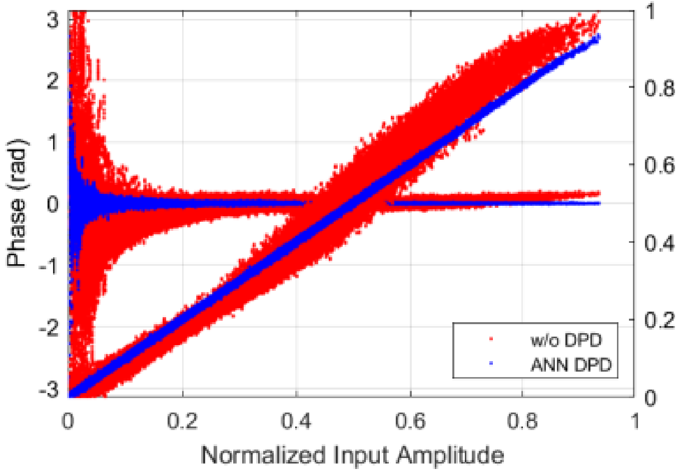
	NMSE [dB]	ACPR [dBc]	EVM[%]	Pout [dBm]	Eff. [%]
No DPD	-	-24.9	11.8	40.9	44.3
ILC	-44.1	-58.1	1.97	40.3	44.2
Large GMP DPD	-40.7	-50.0	2.02	40.3	44.0
ADI Gen6 DPD	-40.0	-49.4	2.02	40.3	44.3

Experimental Results [3]

- DPD Results: 200MHz NR with 8dB PAR







- ADI ADRV9030
  - 8T8R Transceiver
  - 600MHz-7.2GHz

	Nº of Coeff.	NMSE [dB]	ACPR [dBc]	EVM[%]	Pout [dBm]	Eff. [%]
No DPD/Fixed Phase SP	-	-16.3	-22.6	7.65	40.4	51.0
No DPD/Linear Phase SP	-	-20.9	-28.4	4.75	39.9	50.9
GMP DPD	458	-34.3	-40.3	1.9	40.3	49.7
ANN DPD	1000	-40.1	-46.5	1.8	40.3	49.5

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Conclusions

- MISO Highly Efficient PAs will find applications in broadband radios
- Dual-input Doherty enhances further the bandwidth and maximizes efficiency
- PD-LMBA is a promising broadband PA architecture but still present some challenges to Digital Predistortion technics
- Shaping function optimization is crucial for MISO loaded power amplifier linearization

Next Steps

- Investigate more shaping functions for MISO PAs
- Demonstrate Highly efficient PAs with BW > 400MHz
- Enhanced DPD architecture for MISO loaded modulated power amplifiers

References

[1] W. H. DOHERTY, “A new High Efficiency Power Amplifier for Modulated Waves”, Proceedings of the IRE, Vol. 24, Number 9, Sept. 1936

[2] D.J. Sepphard, J. Powell, and S C. Cripps, “An Efficient Broadband Reconfigurable Power Amplifier Using Active Load Modulation”, IEEE Microwave & Wireless Components Letters, Vol. 26, No. 6, June 2016

[3] Yuchen Cao and Kenle Chen, "Pseudo-Doherty Load-Modulated Balanced Amplifier with Wide Bandwidth and Extended Power Back-Off Range", IEEE Transactions on microwave theory and techniques, vol. 68, no. 7, July 2020

[4] Wantao Li and al. “Digital Shaping and Linearization of a Dual-Input Load-Modulated Balanced Amplifier” , 2023 International Workshop on Integrated Nonlinear Microwave and Millimetre-Wave Circuits (INMMIC)

[5] D. R. Morgan, Z. Ma, J. Kim, M. G. Zierdt and J. Pastalan, "A Generalized Memory Polynomial Model for Digital Predistortion of RF Power Amplifiers," in IEEE Transactions on Signal Processing, vol. 54, no. 10, pp. 3852-3860, Oct. 2006,

[6] N. Naraharisetti, C. Quindroit, P. Roblin, S. Gheitanchi, V. Mauer and M. Fitton, "2D cubic spline implementation for concurrent dual-band system," 2013 IEEE MTT-S International Microwave Symposium Digest (MTT), Seattle, WA, USA, 2013, pp. 1-4