High Data Rate Modulation of mm-Wave Power Amplifier / Antenna Arrays Using Digital Predistortion

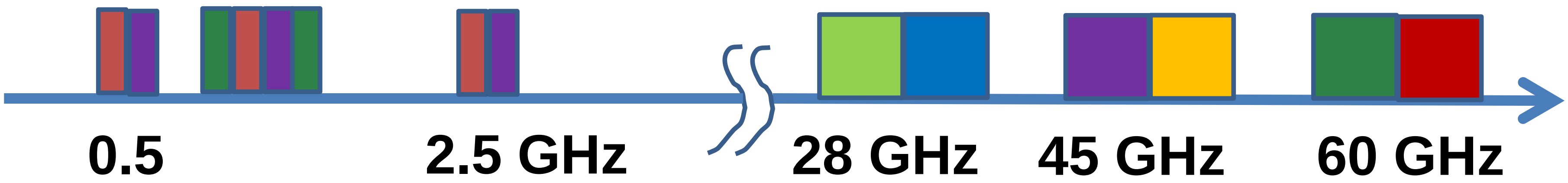
H. Dabag[1,2], B. Hanafi[2], O. Gurbuz[2],
G. Rebeiz[2], J. Buckwalter[2] and P. Asbeck[2]

[1]Qualcomm, San Diego, CA
[2]University of California, San Diego, La Jolla, CA

Industry Requires High Data Rates for Download AND Upload

Cellular band heavily fragmented.

K_a, Q, and U-band allow channels of >> 100 MHz



To provide high data rates to users we need:

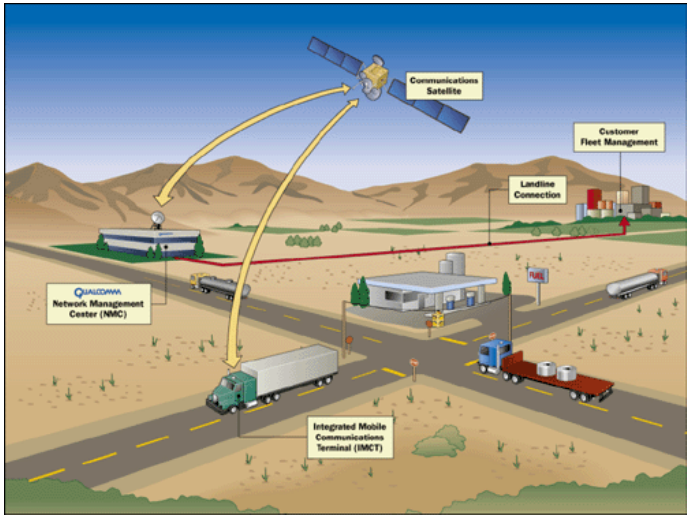
Non-Contiguous Inter-band Carrier Aggregation

Challenges with both these approaches!

WiGig: Gb/s at mm-waves

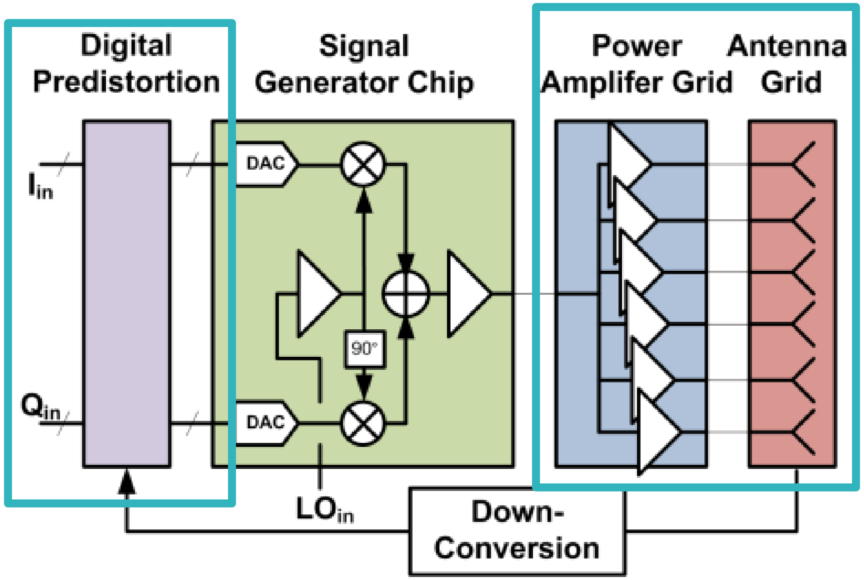
- Most reports of 1-10 Gb/s systems use low complexity modulations e.g. QPSK with low spectral efficiency!
- Once we have many mm-wave users, we do need to share the available spectrum at mm-waves.

Achieving high spectrally efficient Gb/s at mm-waves using 1024-QAM and DPD.



Outline

- Stacked-FET PAs
- Spatial power combined PAs
- Wideband DPD system
- High Complexity Constellations
  - DPD of PA array
  - EVM and ACPR vs. Pout
  - BER vs. Pout and EVM
- Conclusion

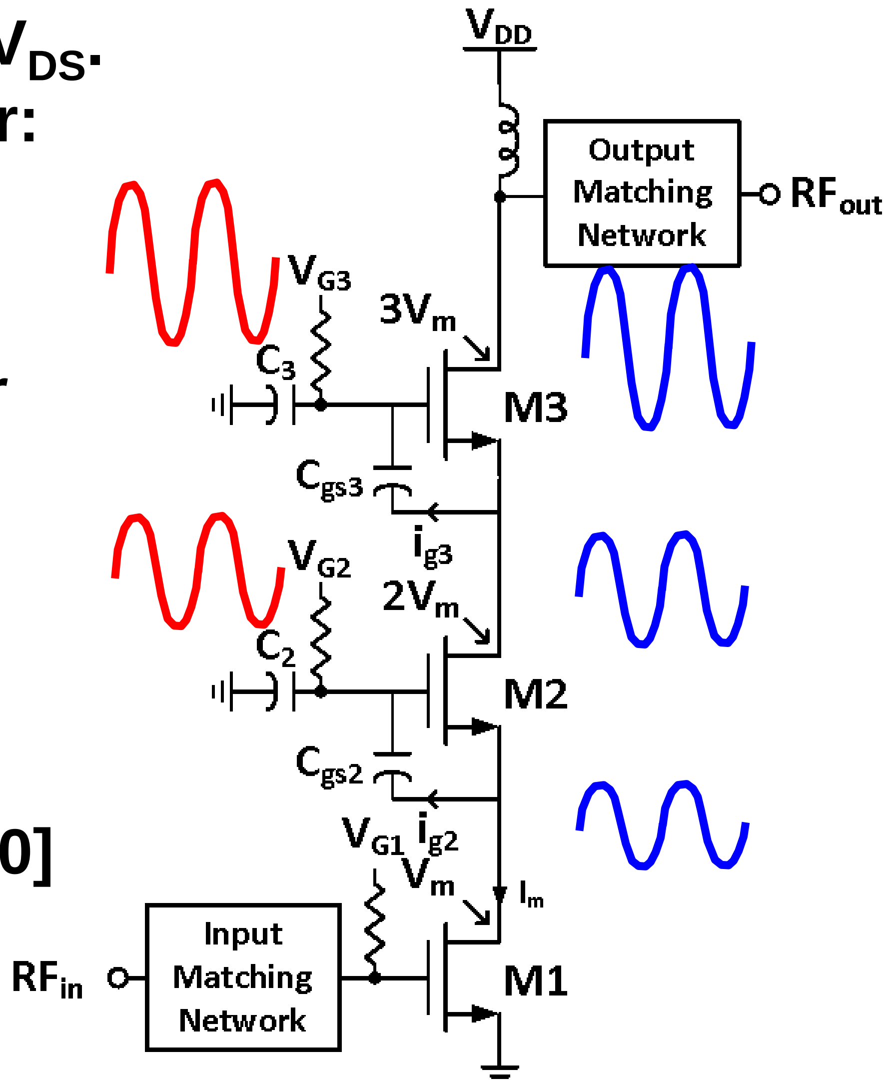


The Stacked-FET PA Technique

- ***K*** **stacked FETs allows** ***K*** **x** BV_{DS}**.**
  At least K times higher power:
  $P_{out} = K \cdot BV_{DS} \cdot I_m$

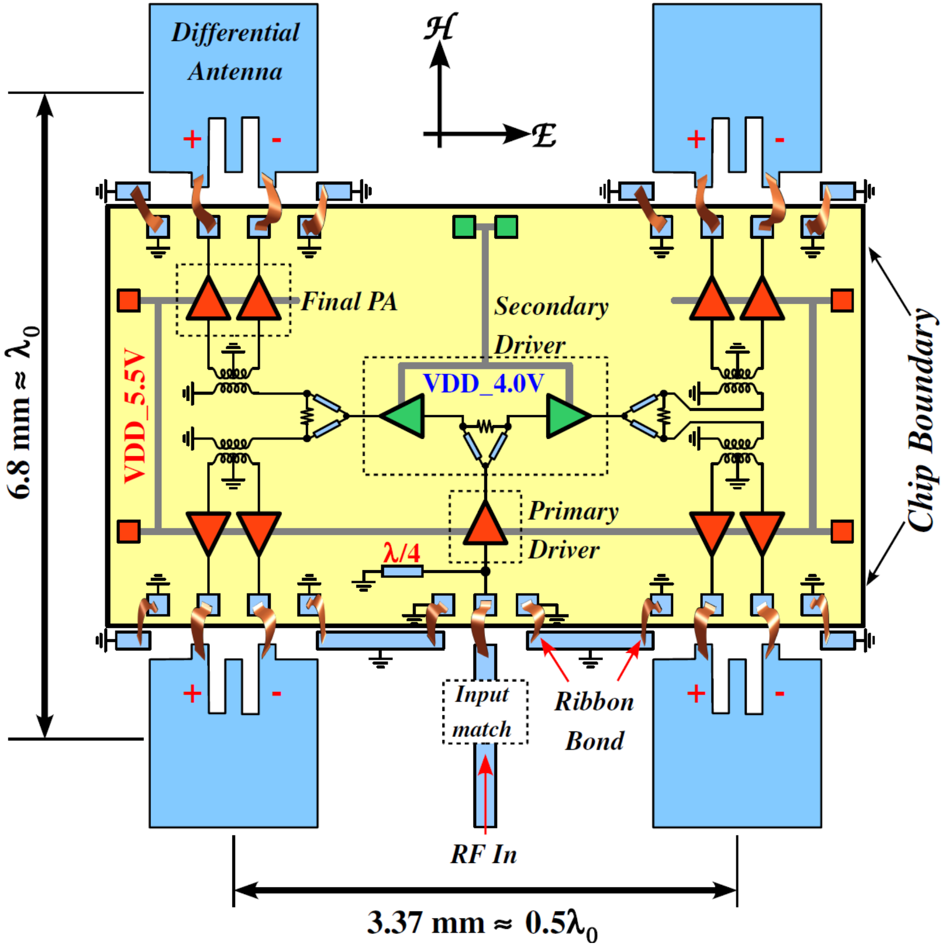
This has been studied for cellular frequencies 1-2 GHz and more recently for mm-waves.

A. Ezzeddine et al. **[RFIC 2003],**
J. Jeong et al. **[MWCL 2006],**
S. Pornpromlikit et al. **[T-MTT 2010]**
A. Balteanu et al. **[JSSC 2013]**



45 GHz 2x2 Antenna / PA Array
Bassel Hanafi [IMS 2014]

- On chip
- 8 PAs: 4-stack
- 3-stack drivers
- On board Wilkinson dividers
- Differential PCB patch antennas
- 2x2 array



45 GHz 2x2 Antenna / PA Array
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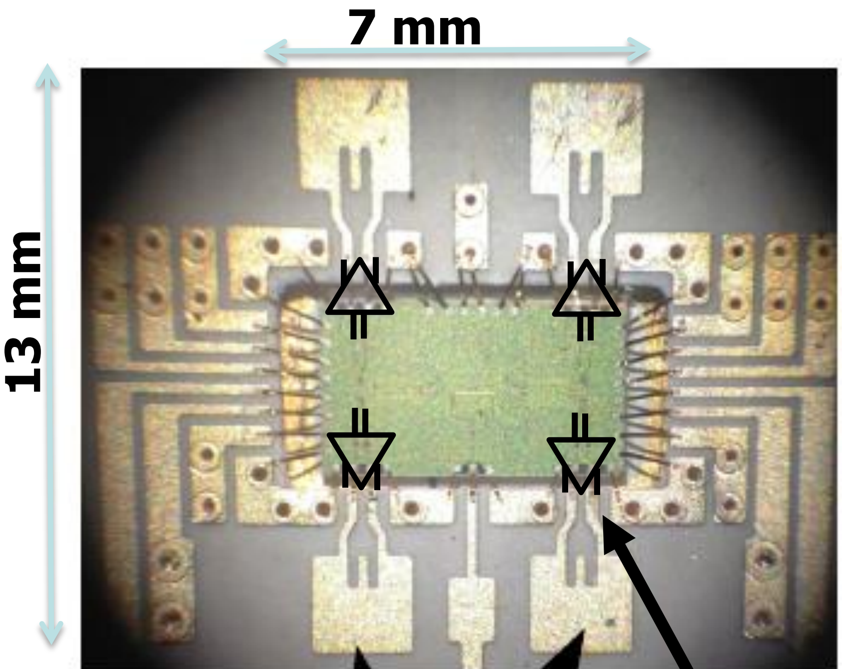
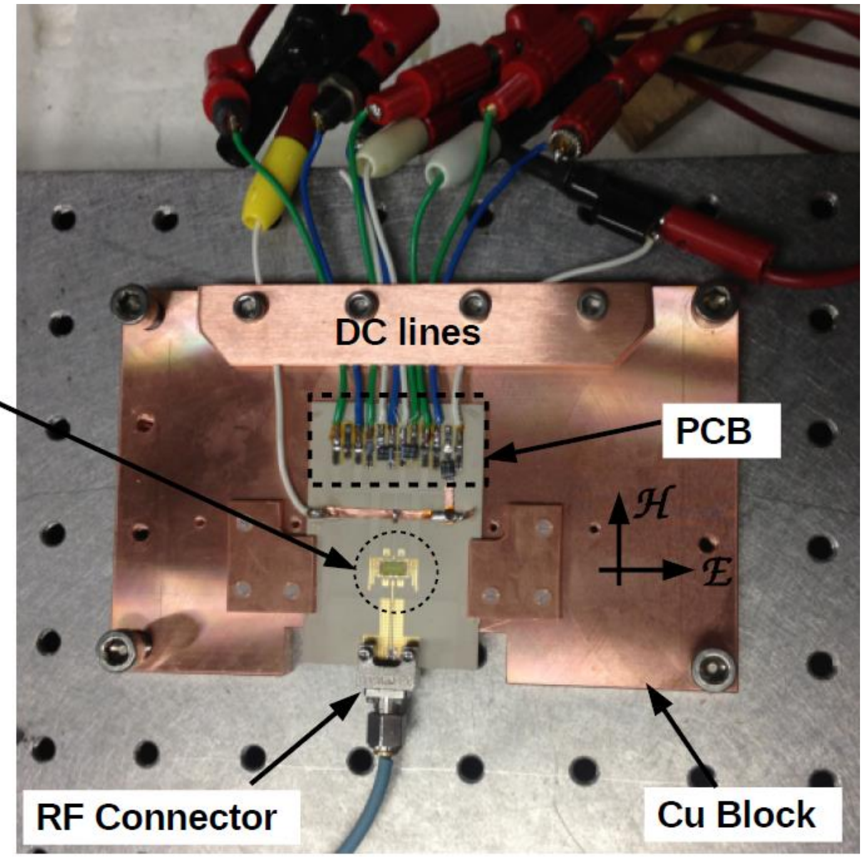


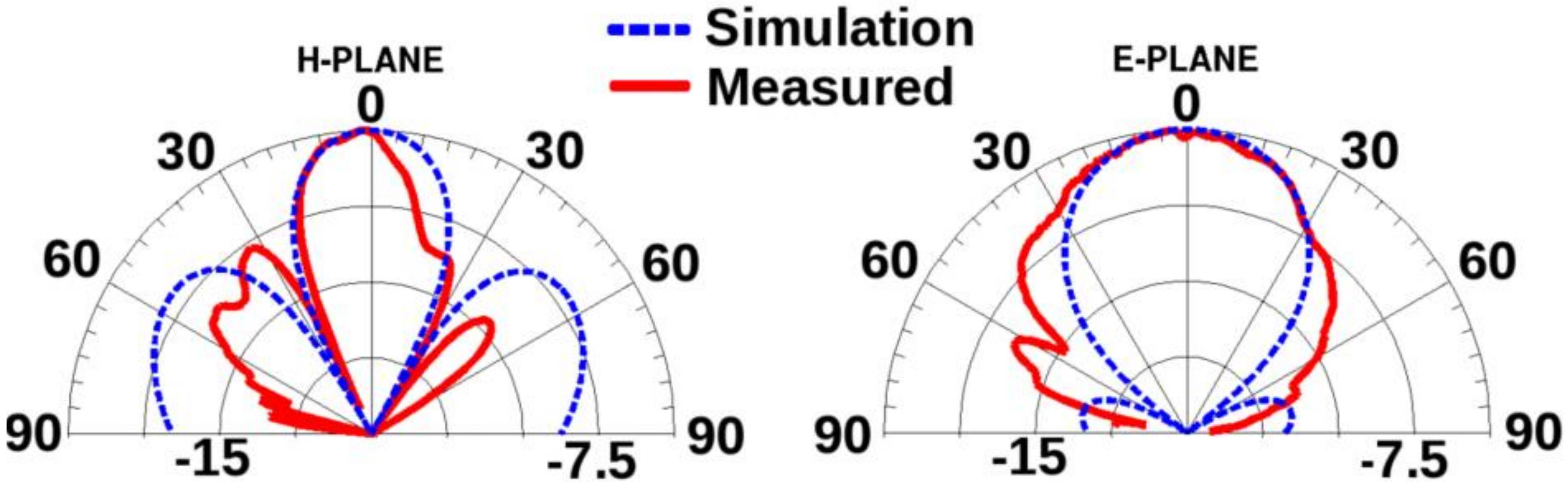


Differential Antenna + MN

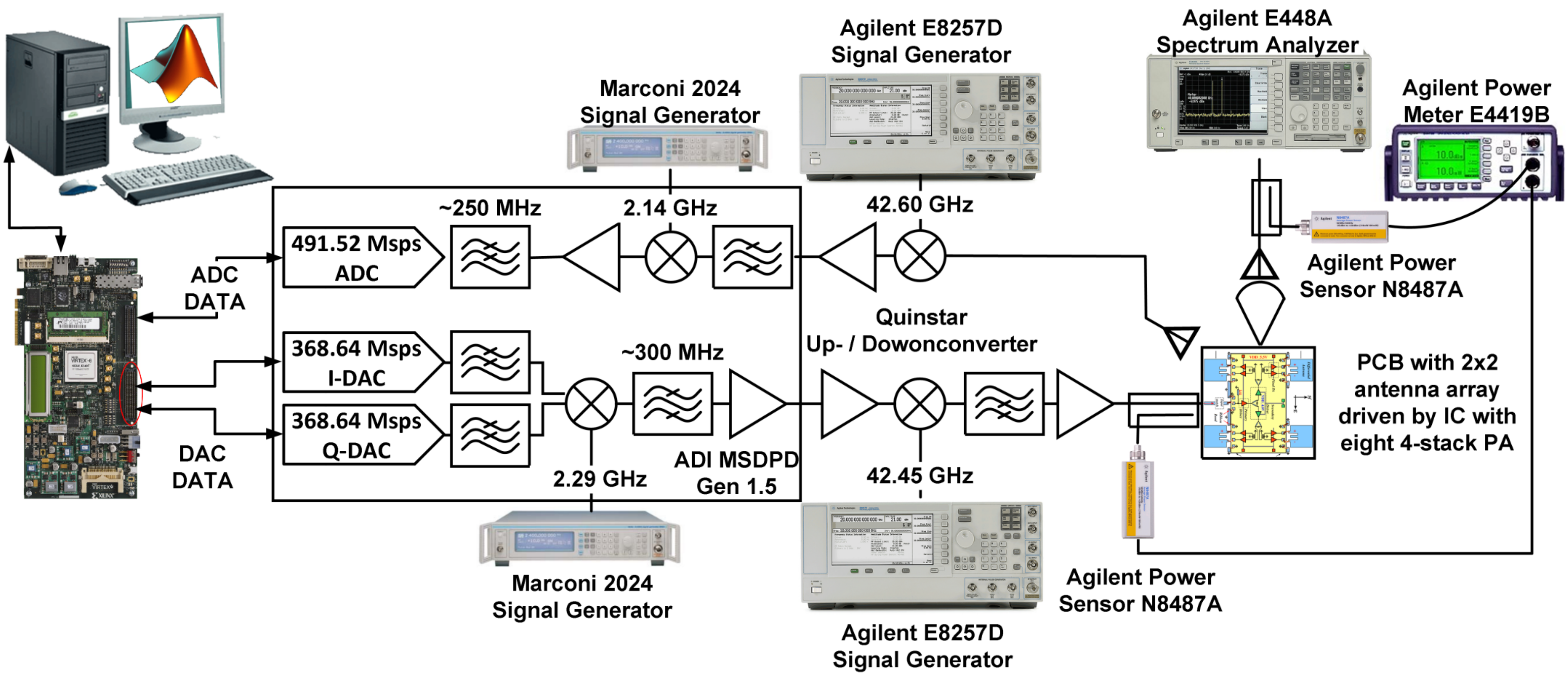
8 x 4-stack unit amplifier
H. Dabag [T-MTT 2013]

Measured Patterns

- Array Gain $G_{TX} \approx$ 10-12 dB
- Grating lobes in H-plane
  - Measurements prone to reflections/scattering



Mark E Predistortion System

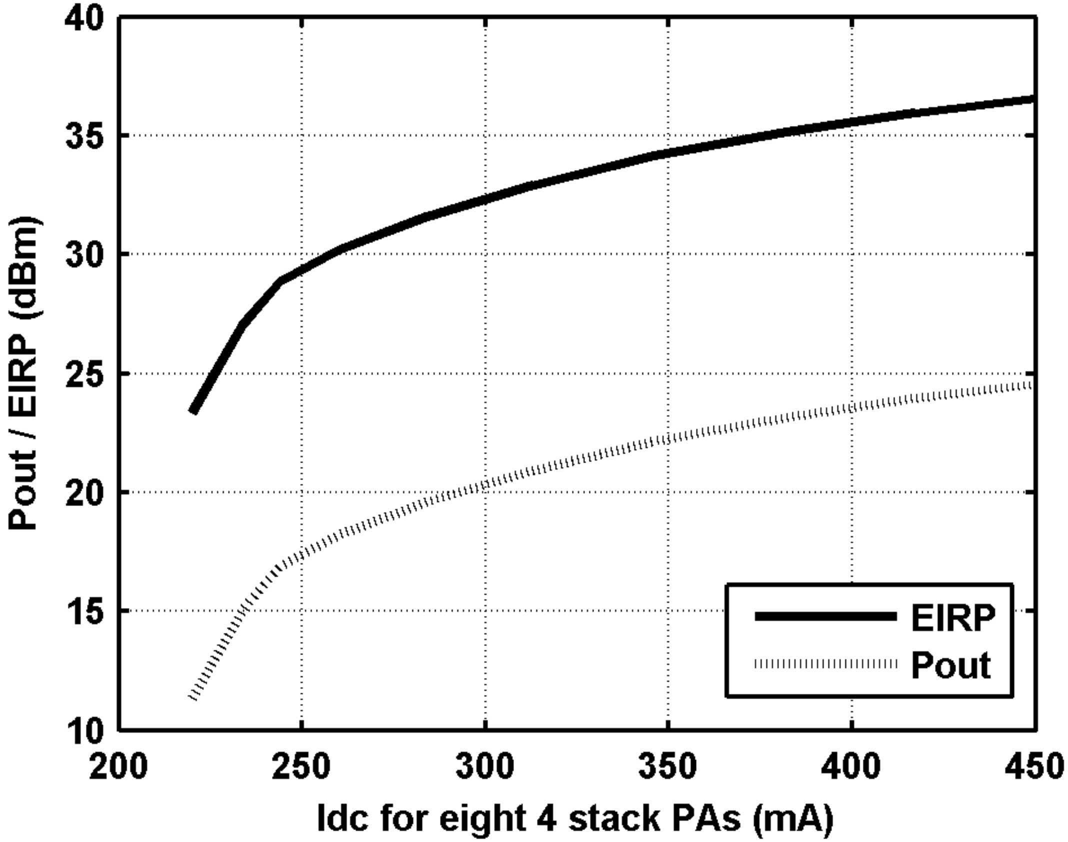


DPD bandwidth ~250 MHz

EIRP* vs. I_{DC} for CW Test

$$EIRP = P_{at\ RX\ antenna} - G_{RX\ antenna} - \text{Path loss}$$

$$P_{out} = EIRP - G_{TX\ antenna}\ (\sim 12\ dB)$$



*equivalent isotropically radiated power (EIRP)

DPD Algorithms: Memory Polynomial and Generalized Memory Polynomial

$$y_{\mathrm{GMP}}(n) = \sum_{k=0}^{K_a-1}\sum_{l=0}^{L_a-1} a_{kl}x(n-l)\left|x(n-l)\right|^k$$

Terms used in "MP"

$$+\sum_{k=1}^{K_b}\sum_{l=0}^{L_b-1}\sum_{m=1}^{M_b} b_{klm}x(n-l)\left|x(n-l-m)\right|^k$$
$$+\sum_{k=1}^{K_c}\sum_{l=0}^{L_c-1}\sum_{m=1}^{M_c} c_{klm}x(n-l)\left|x(n-l+m)\right|^k .$$

Cross terms added in "GMP"

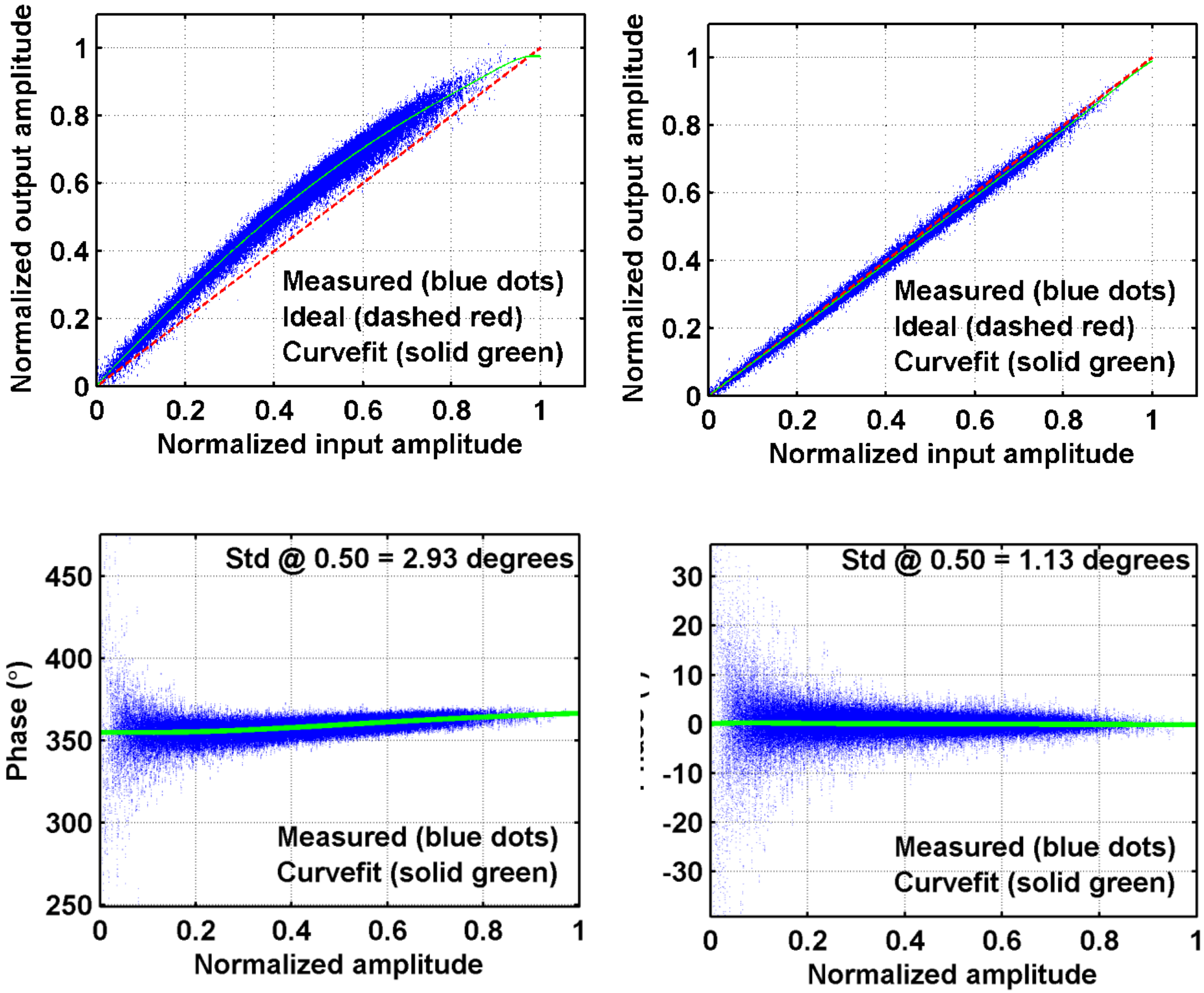
Memory Mitigation

Block iterative procedure that eliminates all deterministic effects (*P. Draxler et al.*)

AMAM and AMPM behavior of the PA array (100 MHz input signal)

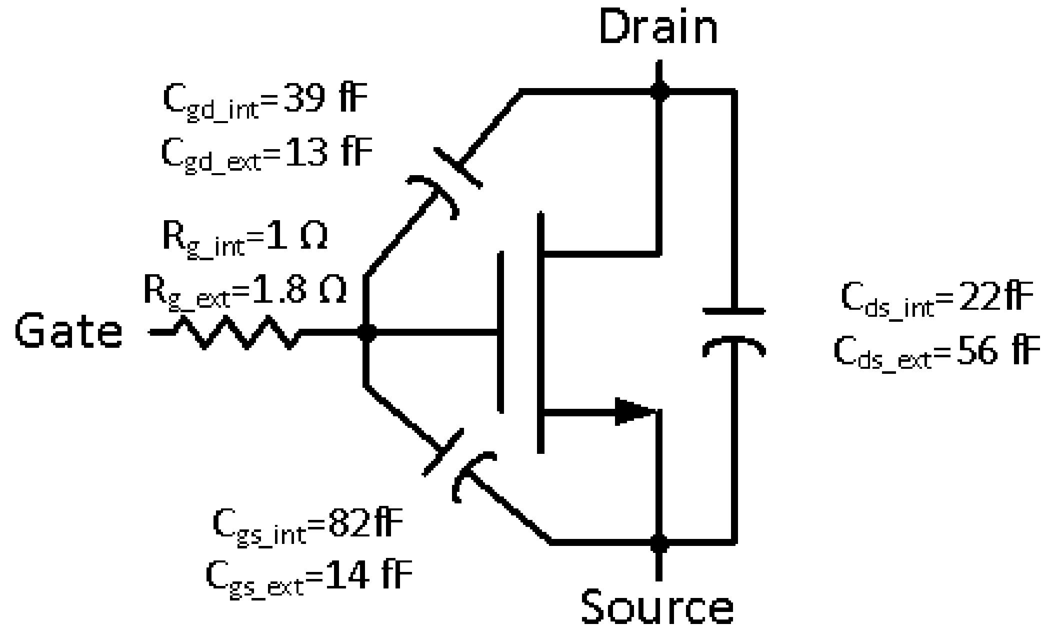
A lot of memory

Very small AM-PM



SOI FET Parasitics

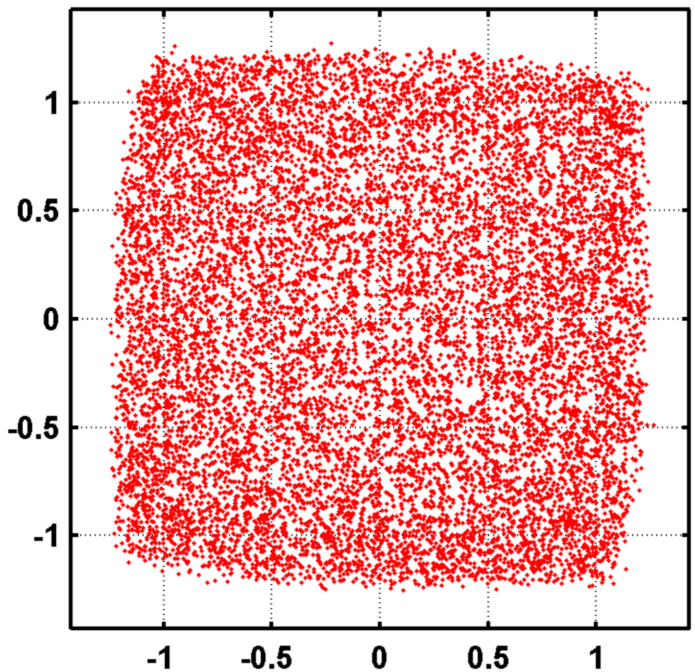
- Significant intrinsic C_{gd} and significant C_{ds}
- Simulation show that ext C_{gd} reduces AM-PM



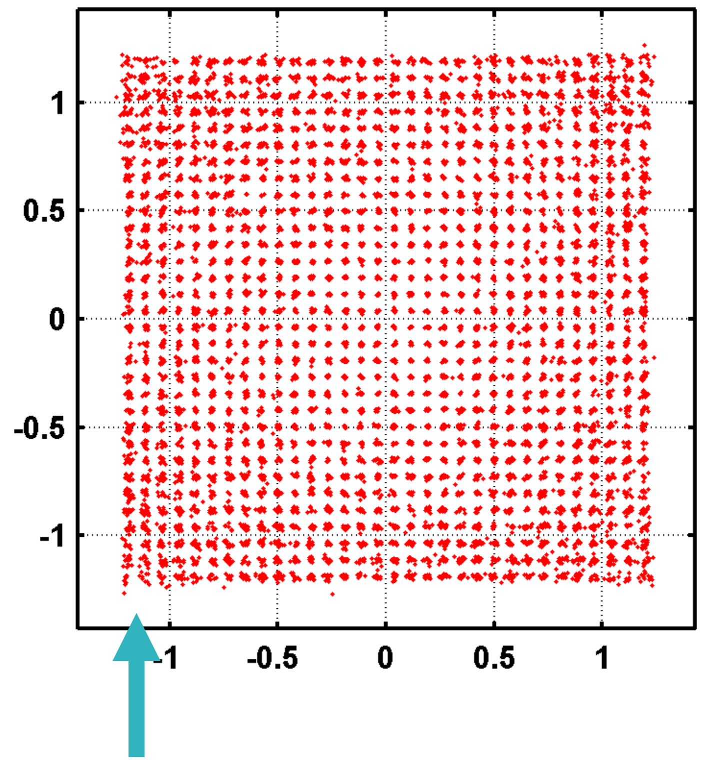
For a 150 µm wide device

2x2 Array at 45 GHz; 98 MS/s, 1024 QAM, 0.98 Gb/s

No DPD
EIRP = 27.9 dBm
EVM = 6.4%

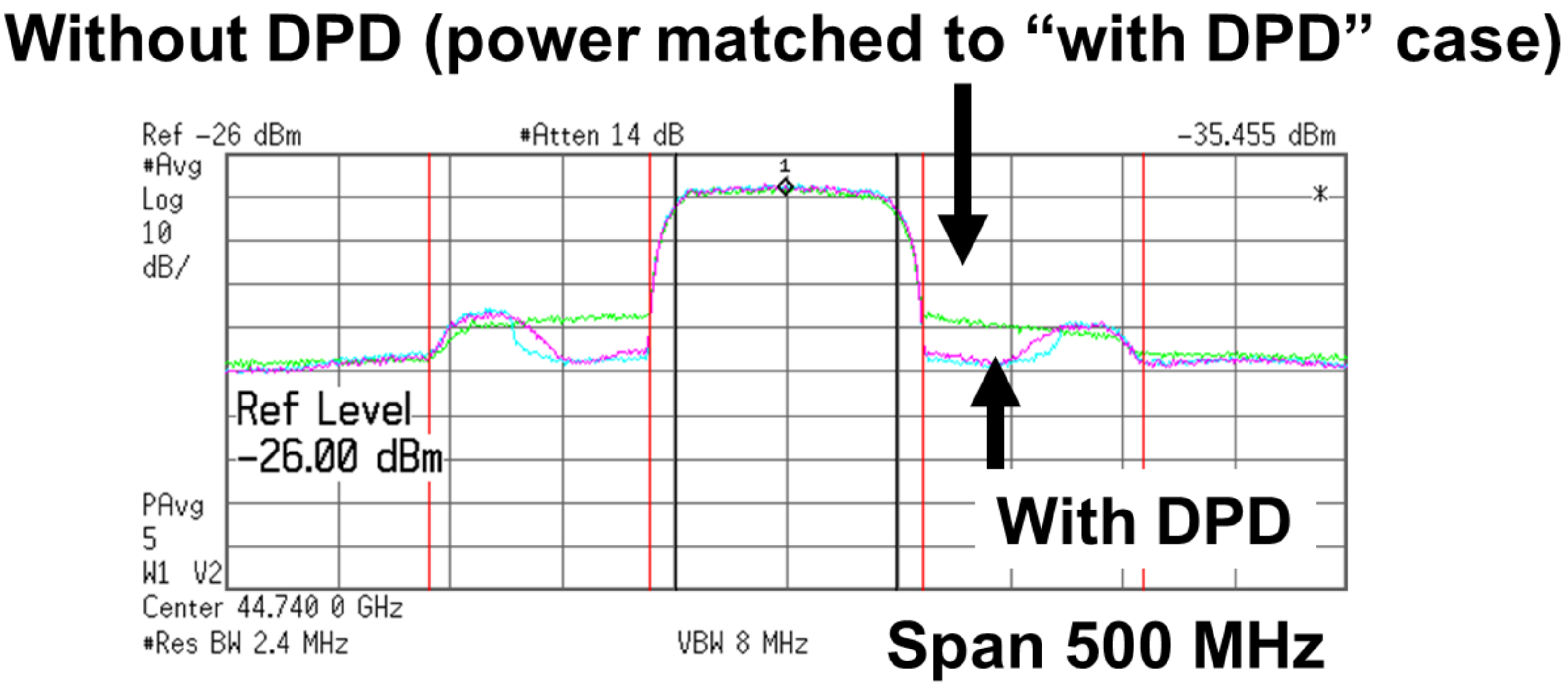


With DPD; 181 coefficients
EIRP = 26.2 dBm
EVM = 1.3%



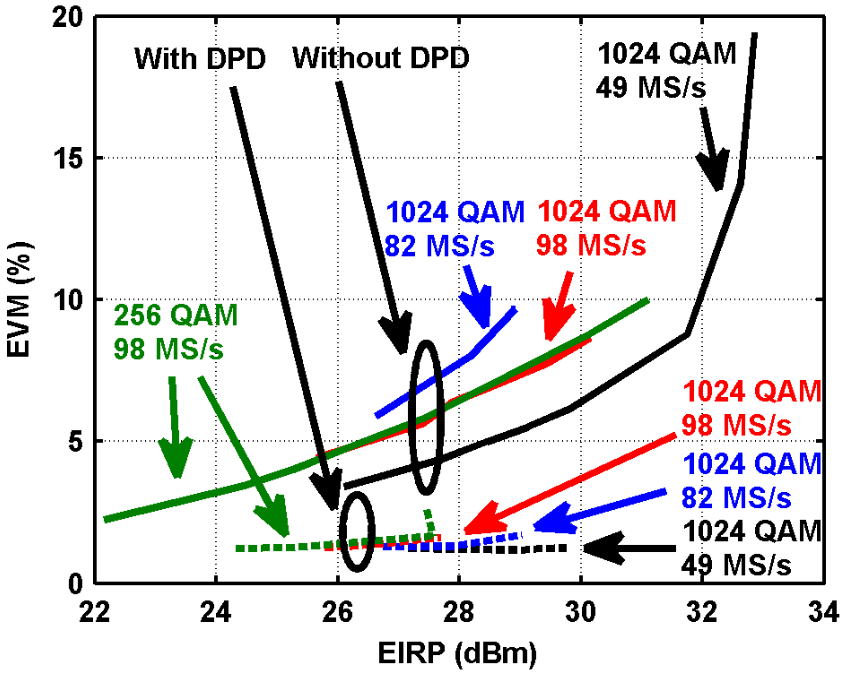
Likely bit errors at the corner

2x2 Array at 45 GHz; 98 MS/s, 1024 QAM, 980 Mb/s



EIRP = 26.2 dBm	Before DPD	After DPD
ACPR (dBc)	-29.4	-32.3
ACPR within DPD BW (dBc)	~-29	~-37

EVM vs. Pout



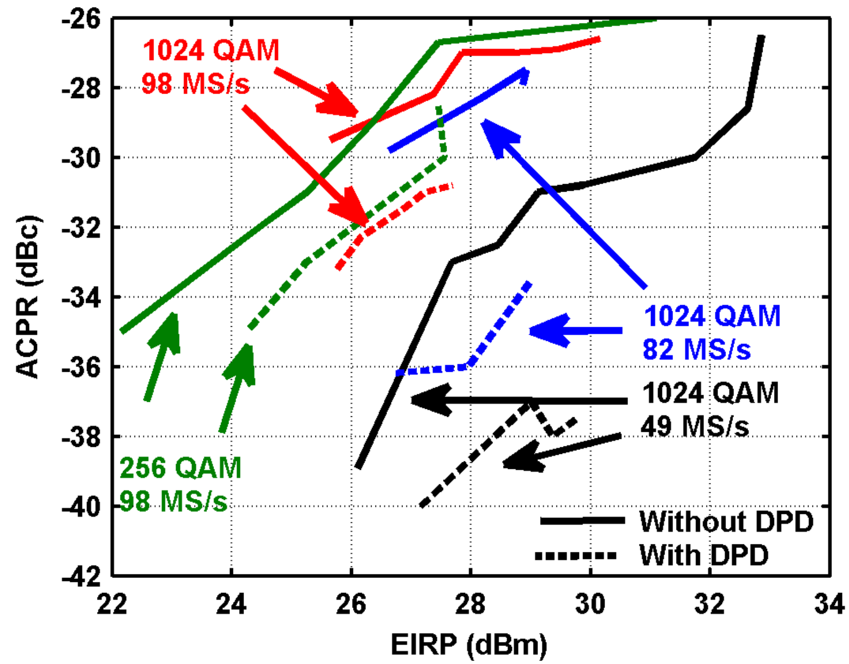
Modulation	BW (MHz)	EVM (%)	EIRP (dBm)
1024-QAM	50	1.3	29.8
	80	1.3	27.9
	100	1.3	26.2
256-QAM	100	1.6	27.6

- Can achieve comparable EVM for all signals after DPD.
- Marginal EVM improvement by reducing power (after DPD)

- Maximum EIRP from CW test ~ 36 dBm;
- PAPR ~7 dBm

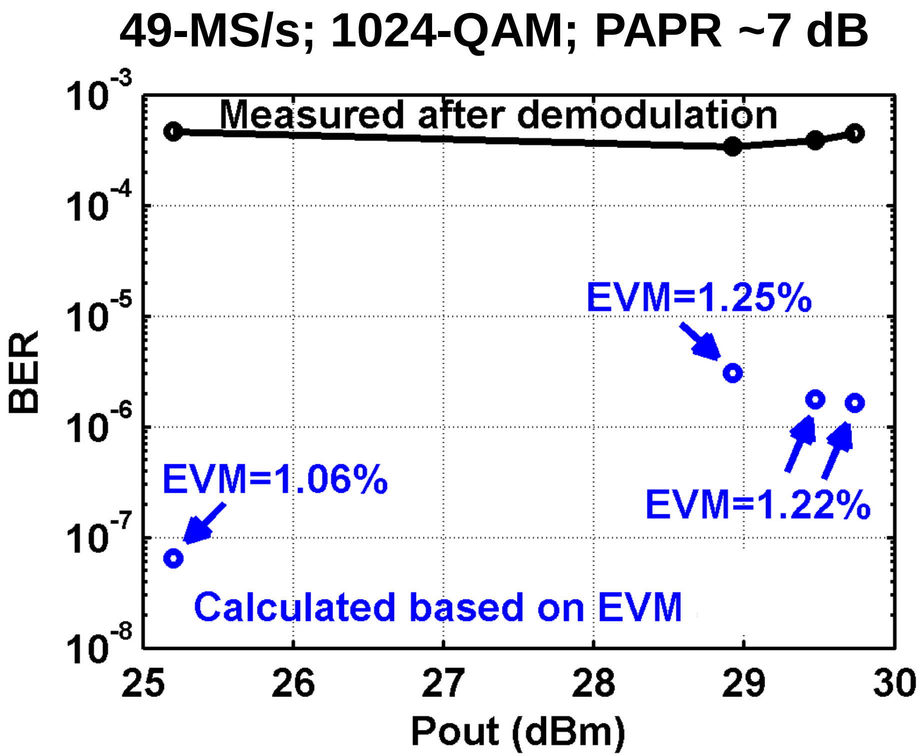
ACPR vs. Pout

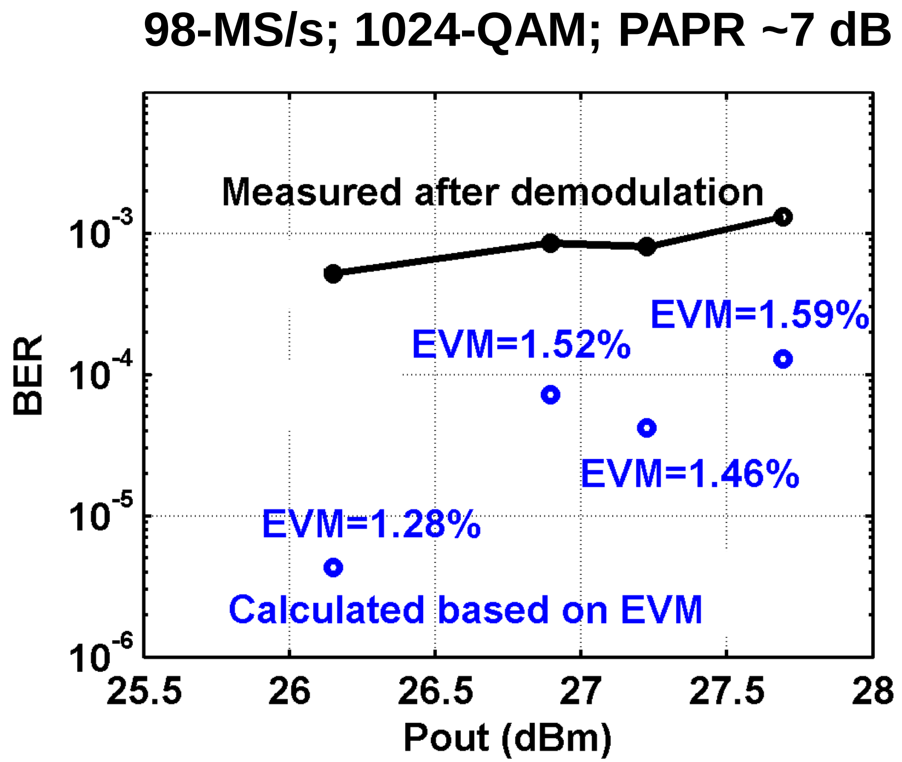
Modulation	BW (MHz)	EVM (dB)	EIRP (dBm)	ACPR (dB)
1024-QAM	50	-37.7	29.8	-38
	80	-37.7	27.9	-36
	100	-37.7	26.2	-32.3
256-QAM	100	-35.9	27.6	-32.3



- ACPR is very good after DPD for 50-MHz signal
- ACPR cannot be improved beyond ~-32 dBc for 100 MHz signal, because the DPD BW is limited.
  Within DPD BW ACPR is ~-38 dBc

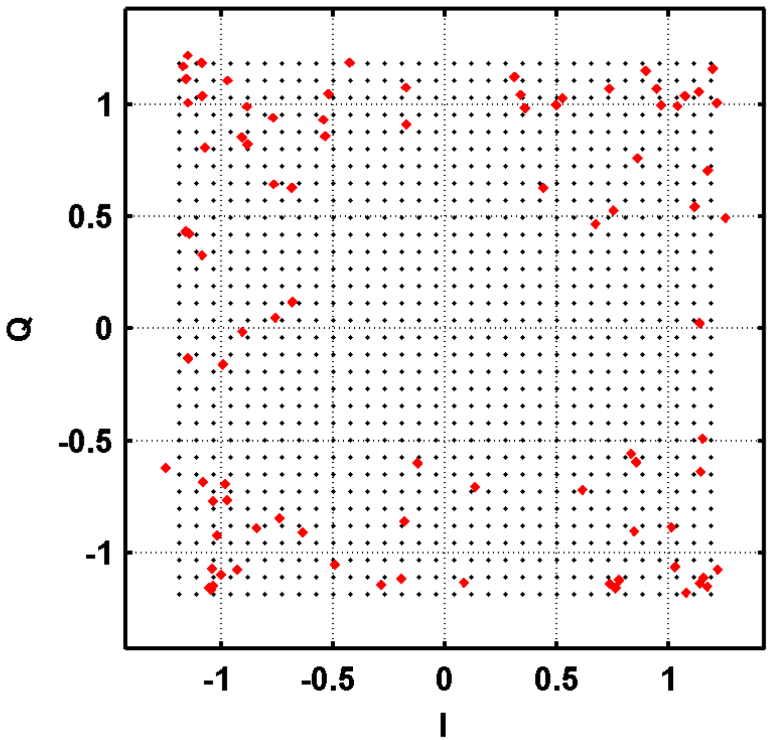
Measured and expected BER vs. EVM (and Pout)

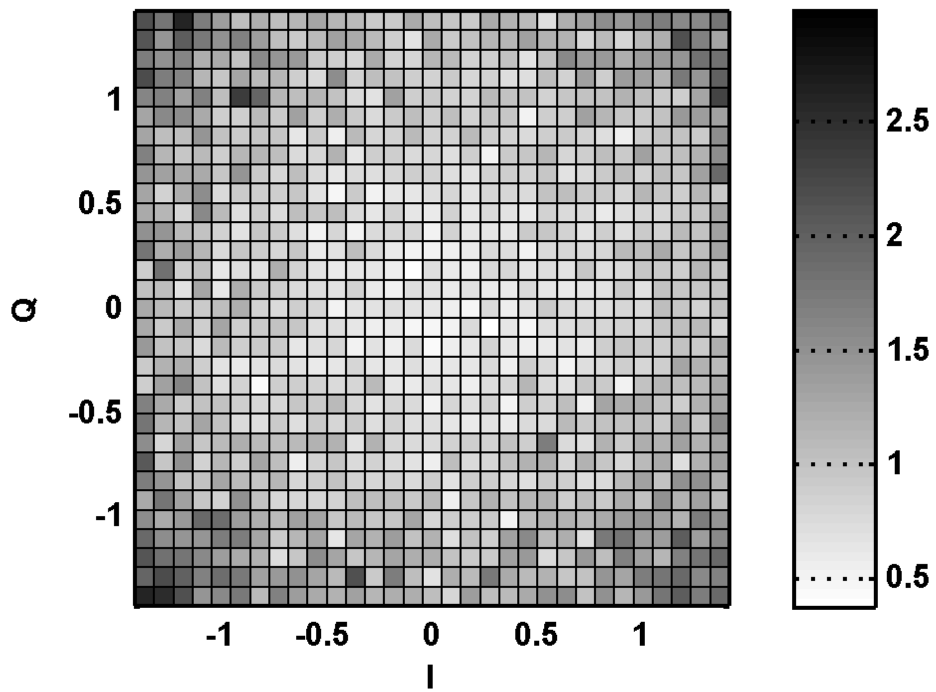




- 29 dBm+7 dB = 36 dBm ~ Psat from CW test
- BER significantly higher than expected, based on AWGN prediction
- BER does not improve as much as expected with better average EVM
- 1024-QAM; 98-MS/s: reducing Pout by ~1.5 dB improves BER by ~2.

Locations of BER for 98-MS/s 1024-QAM at EIRP of 26.2 dBm.





- BER are gathered around edges.
- EVM unequally distributed across constellation

Future Work
Optimized Constellations?

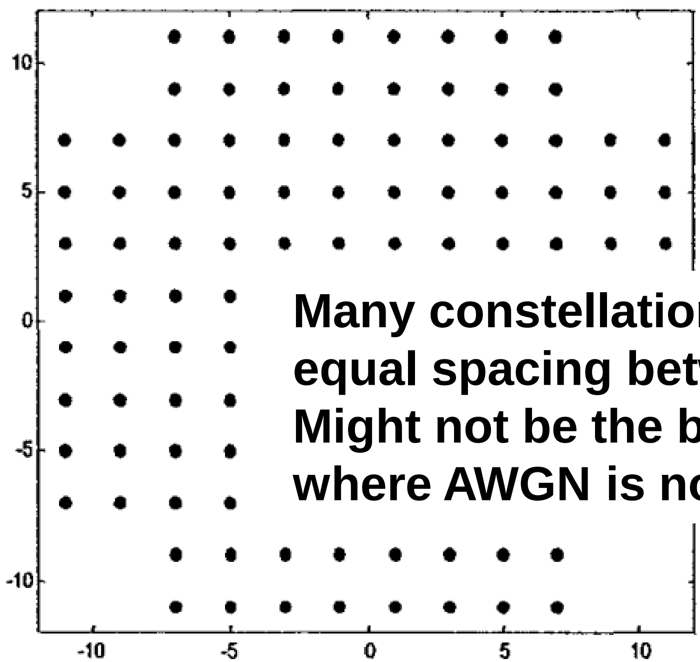


Fig. 5.15: Cross 128QAM constellation

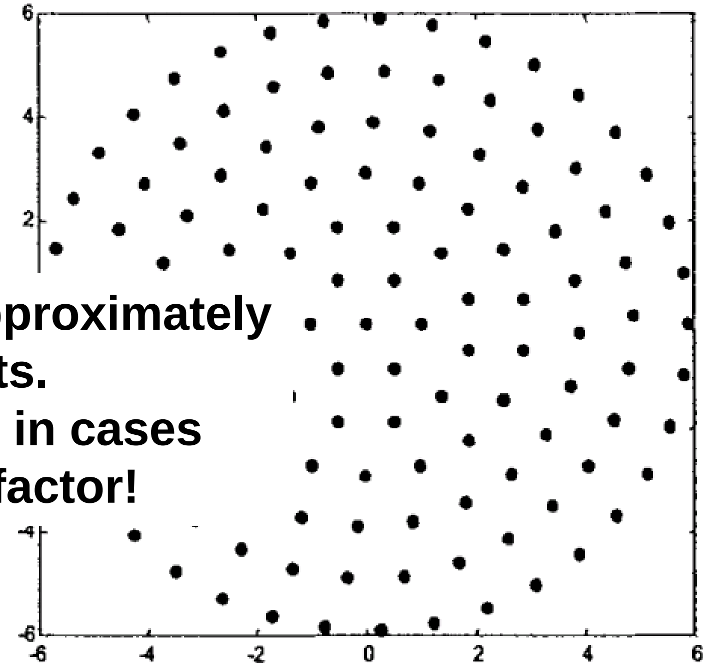


Fig. 5.16: (37,30,24,18,12,6,1)APK constellation

Many constellations have approximately equal spacing between points.
Might not be the best choice in cases where AWGN is not limiting factor!

T. Vo, **"Adaptive Polynomial Predistorters and low-PAR circular APK Signaling Schemes for Systems Using Non-linear Power Amplifiers",** ***Master Thesis from Concordia University*****, 2002**

Summary / Conclusion

- Spatial power combined 8 stacked-PAs
- Stacked-FET PAs in SOI process can be predistorted to high accuracy:
  - Stacking of transistors
  - Floating body effect
  - Power combining of many PAs
- BER vs. P_{out} after DPD:

  -1.5 dB for 0.5x BER: worth it?
- Bit error cluster at edges for 1024-QAM
- Need to re-think constellation:
  - Circular at the edges, square in the center?