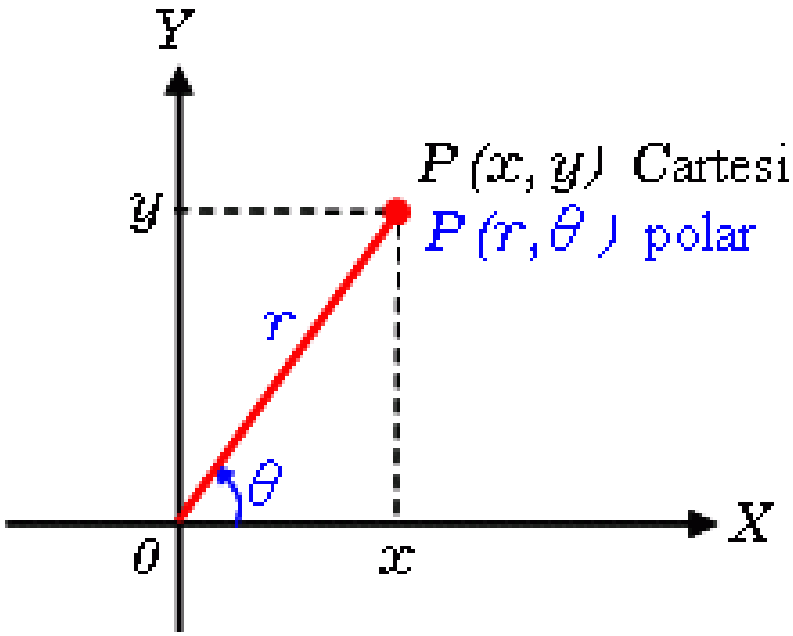
High-Efficiency Transmitter Radio Architectures

- **Envelop and phase BW expansion**
- **Polar Tx**
- **Outphasing Tx**
- **Digital Tx**
- **References**

1) The Polar Tx architecture:



$$x, y = I \ \& \ Q \ \rightarrow Cartesian\ (DCT)$$

$$r, \theta = polar$$

→ Split signal into amplitude and phase signals

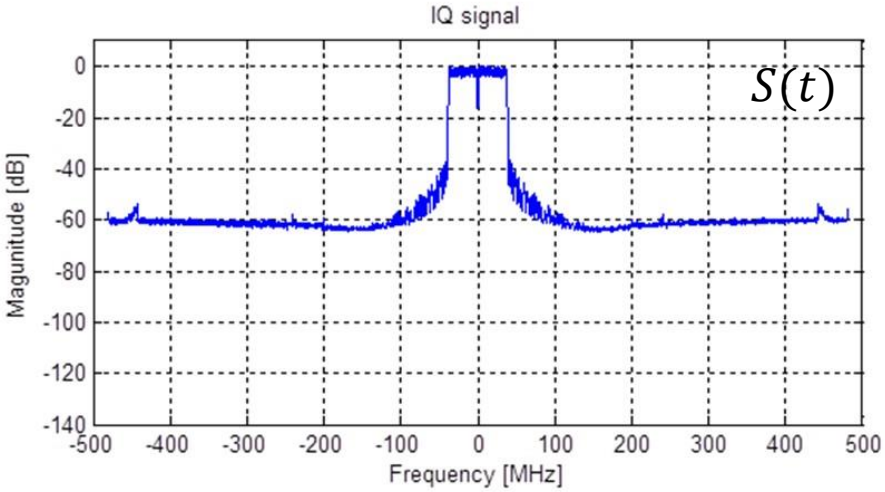
→ Use phase signal to modulate a PLL (for narrowband) or mix with LO (for wideband)

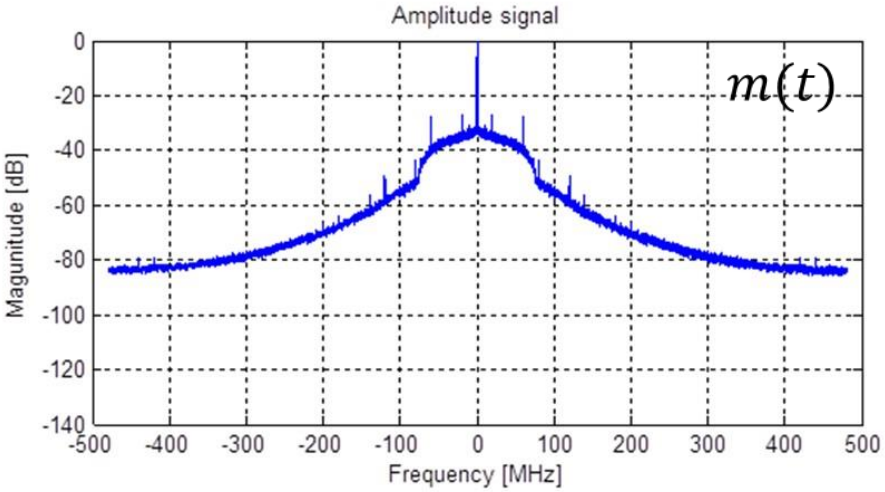
→ Use amplitude signal to control the envelop of the output signal

→ Align both paths to meet target EVM

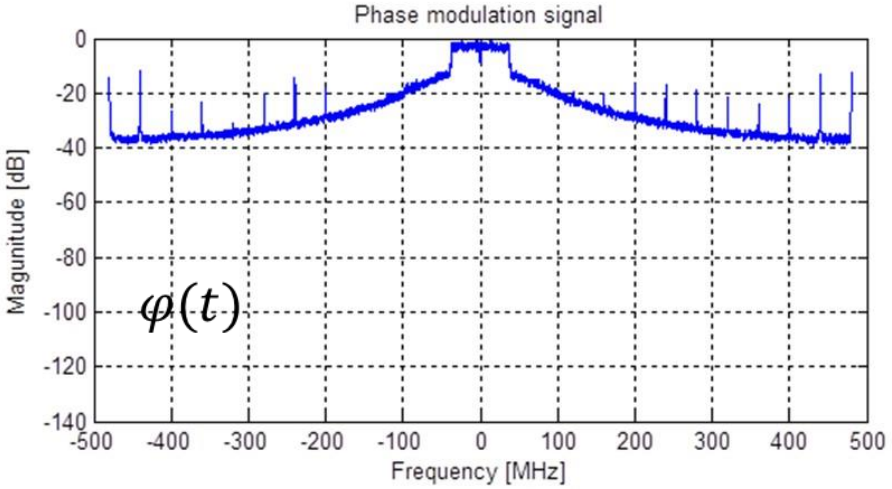
Envelop and phase signal spectrum expansion:

$$S(t) = m(t)\cos(\omega t + \varphi(t))$$

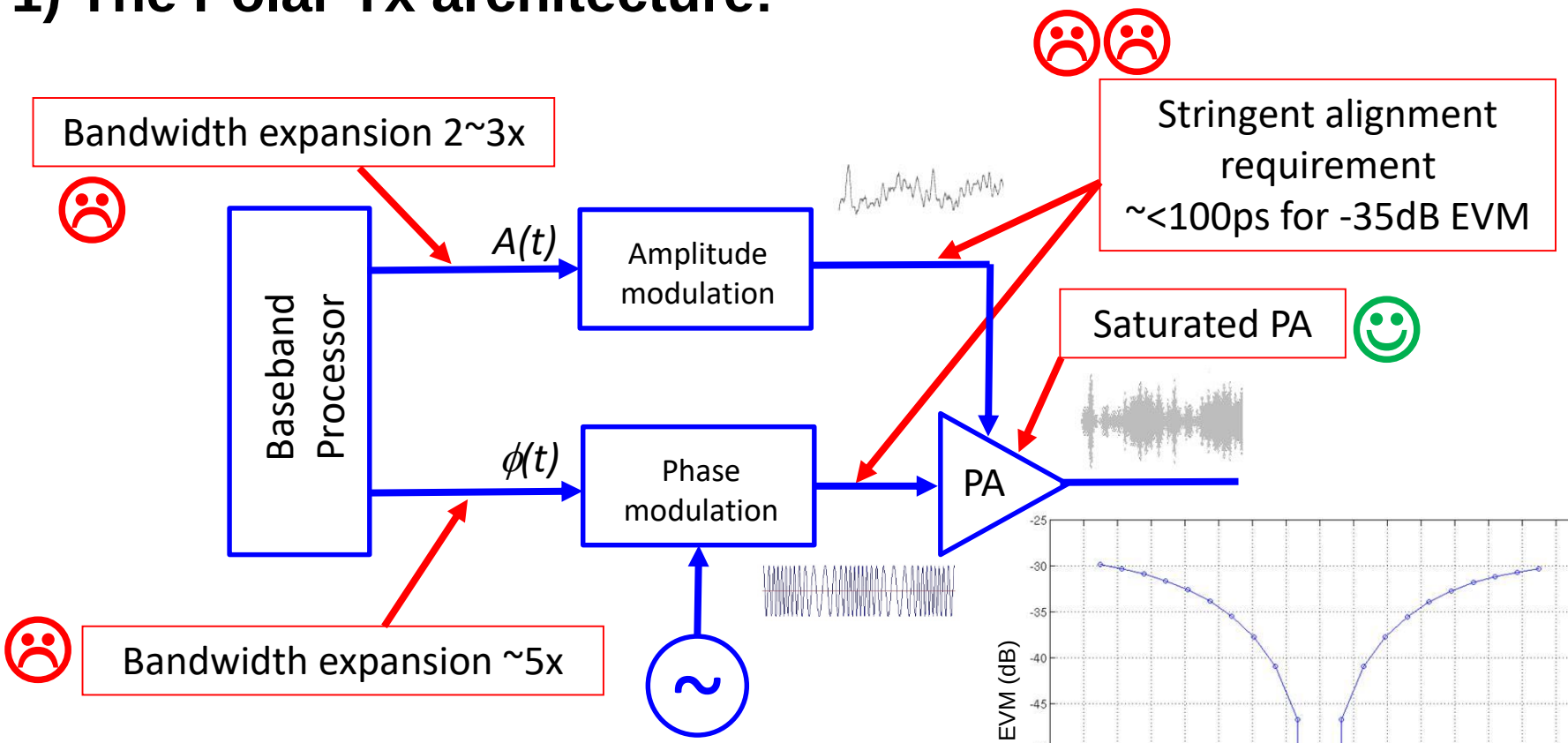




- AM signal BW is ~3x and phase signal BW is 5~7x
- Aligning AM and phase signals is essential to meet target EVM



1) The Polar Tx architecture:

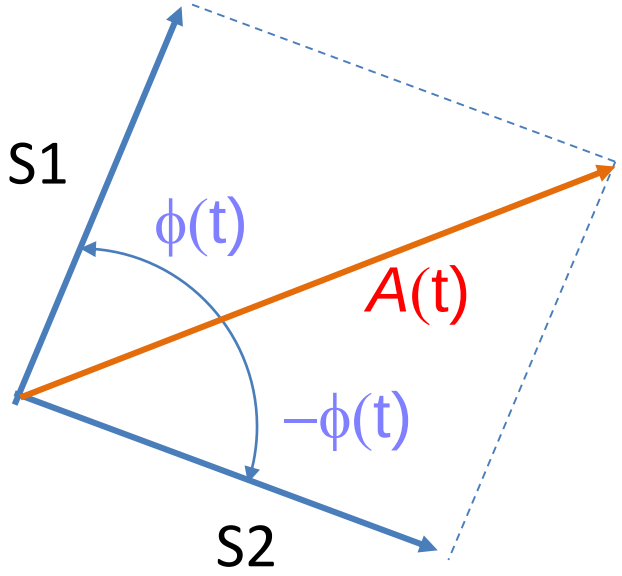


→ Good efficiency for narrowband systems

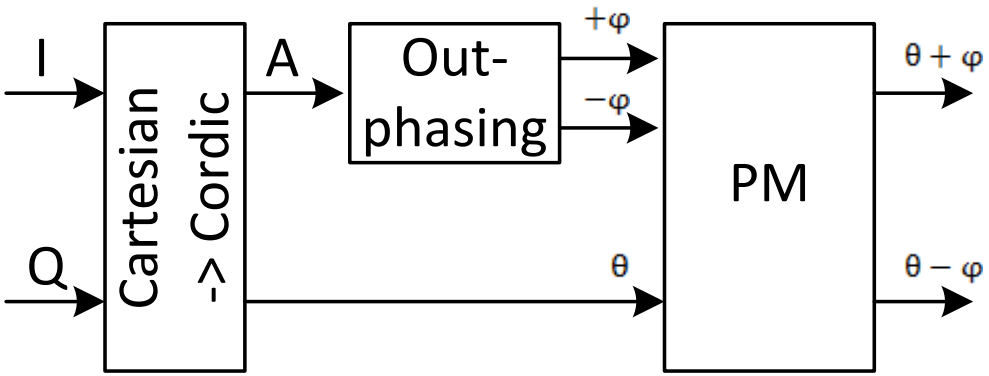
→ System efficiency degrades for large signal BW (>80MHz)

→ Extensive calibrations for BW >160MHz and EVM < -35dB

2) Outphasing Tx architecture:

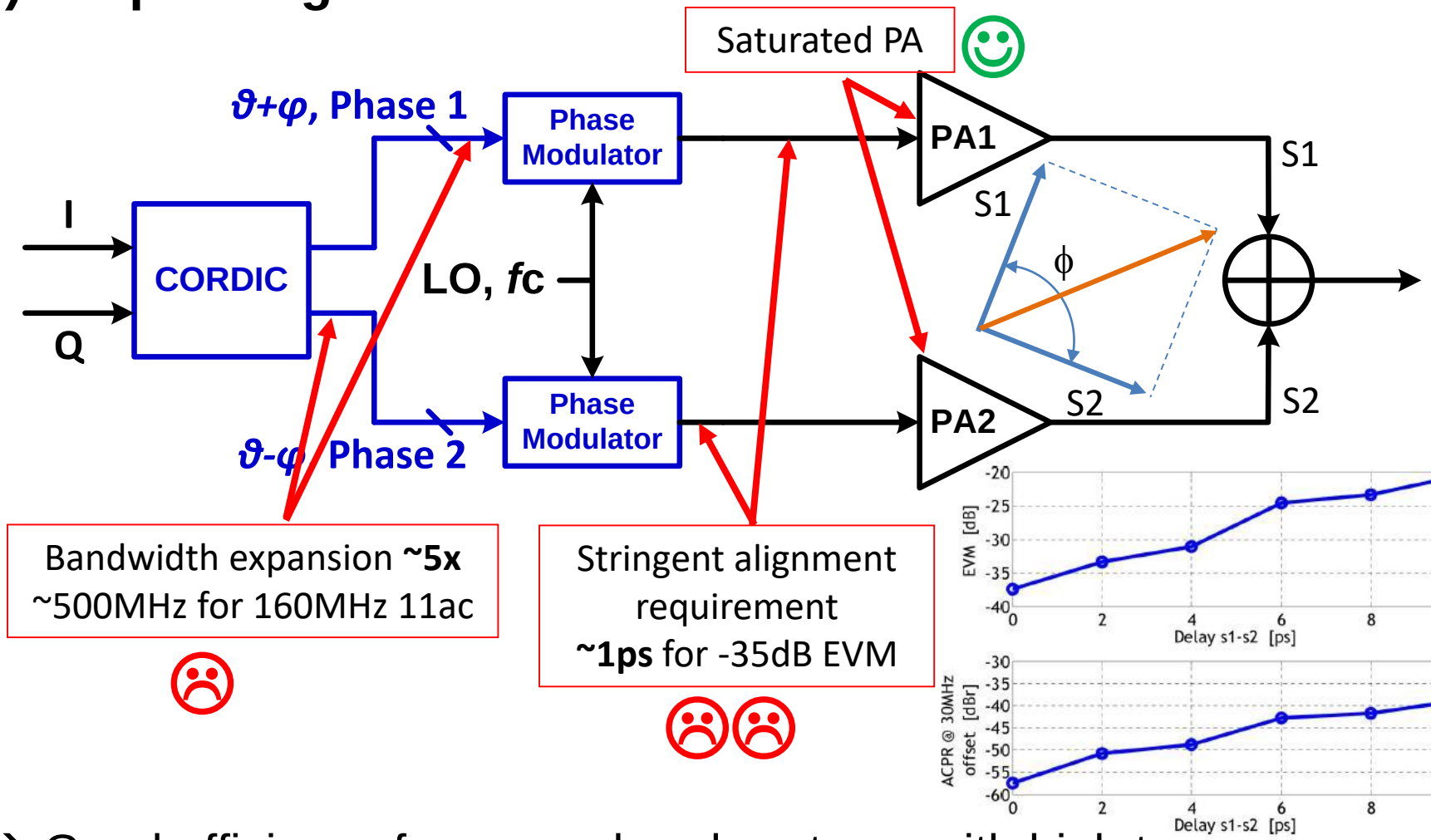


$$S_{1,2}(t) = A_m.cos(\omega_c t + \theta(t) \pm \varphi(t))$$



- → Split signal into two streams of phase-modulated signals and combine (sum) them at the output
- → Adjust relative phase between the two streams to modulate the amplitude of the combined signal *A(t)*
- → Rotate the two streams to realize phase of the modulated sum
- → A saturated PA/Tx is used for each path for best efficiency
- → Align both streams to meet target EVM

2) Outphasing Tx architecture:

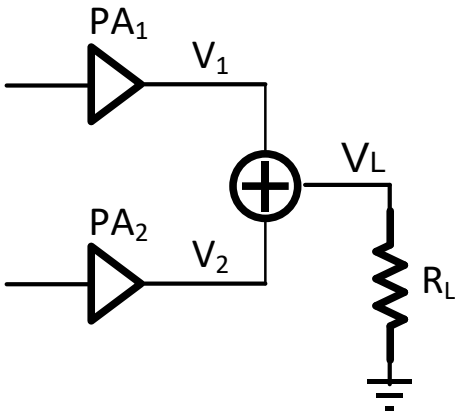


→ Good efficiency for narrowband systems with high to moderate EVM requirements

→ Feasibility is difficult for BW >160MHz and EVM < -35dB

2) Efficiency of Outphasing Tx:

- Ideal outphasing TX uses isolated power combiner.
- Class **B** PA is used for the derivation of efficiency.



For class B PA, supply current is a full-wave rectifier signal

$\rightarrow I_{DC} = 2\frac{I_{pk}}{2\pi}\int_0^{\pi} cos\theta.d\theta = \frac{2I_{pk}}{\pi}$, peak voltage swing is V_{DD}

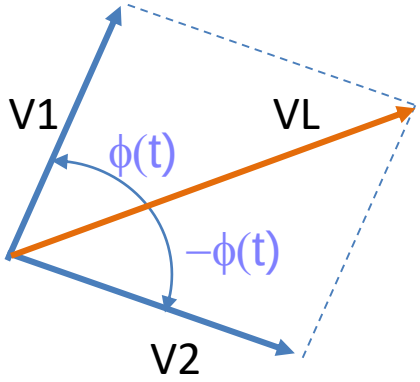
Assuming 1:2 power combiner → each PA sees $R_L/2$ load $\rightarrow I_{pk} = \frac{2V_{DD}}{R_L}$

$P_{DC\_PA} = I_{DC}V_{DD} = \frac{4V_{DD}^2}{\pi R_L}$, but I have two identical PAs → $P_{DC\_tot} = \frac{8V_{DD}^2}{\pi R_L}$

$V_1 = V_{DD}cos(\omega_0 t + \varphi(t) + \theta(t)) = V_{DD}\left(cos(\varphi(t)) + jsin(\varphi(t))\right)$

$V_2 = V_{DD}cos(\omega_0 t - \varphi(t) + \theta(t)) = V_{DD}\left(cos(\varphi(t)) - jsin(\varphi(t))\right)$

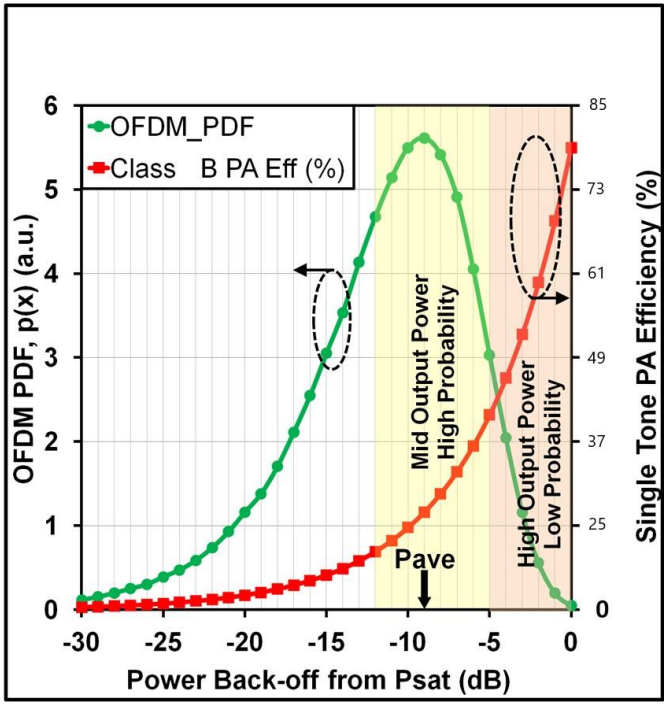
$V_L = V_1 + V_2 = 2V_{DD}cos(\varphi(t))$



$P_{load} = \frac{\left(V_L/\sqrt{2}\right)^2}{R_L} = \frac{2V_{DD}^2 cos^2(\varphi(t))}{R_L} \rightarrow \eta = \frac{P_{load}}{P_{DC}} = \frac{\frac{2V_{DD}^2 cos^2(\varphi(t))}{R_L}}{\frac{8V_{DD}^2}{\pi R_L}} = \frac{\pi}{4}cos^2(\varphi(t))$

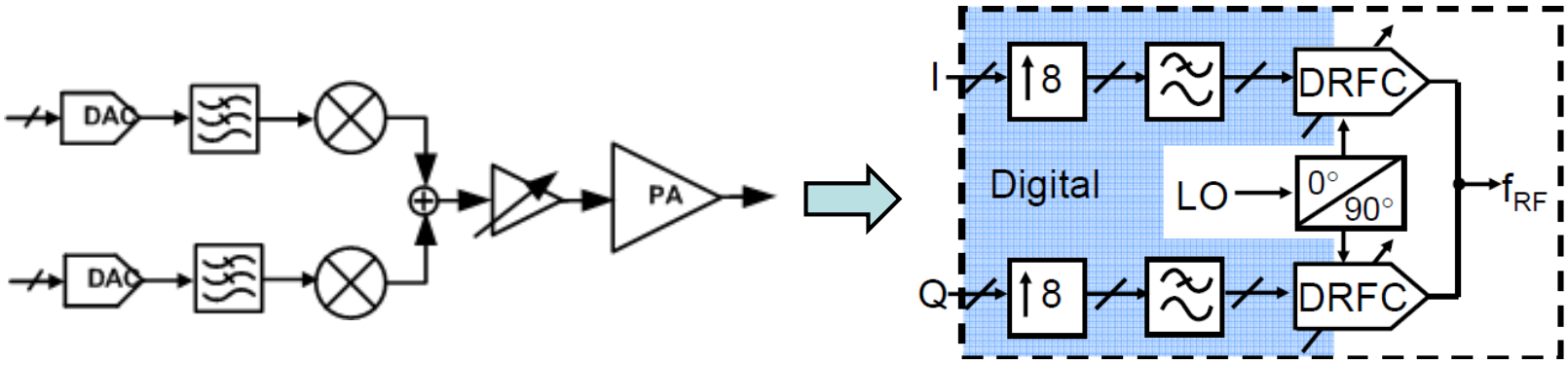
→ Efficiency peaks when the two streams are in phase and is zero when they are out of phase. For modulated signal, you need to calculate this over various phase with probability (one frame)

2) Limitations of of Outphasing Tx:



- → Total Tx efficiency is by calculating the efficiency at each point of the signal amplitude PDF (and the corresponding cos(ϕ(t))) and take the average. Therefore, efficiency is far lower than the one at peak power
- → The two streams can affect each other's linearity due to finite isolation (complicates DPD)
- → Precise gain and phase alignment of the two streams is required
- → Digital Cordec supply current to generate phase signals is a large overhead that dilutes efficiency

3) Digital transmitter: Digital I/Q

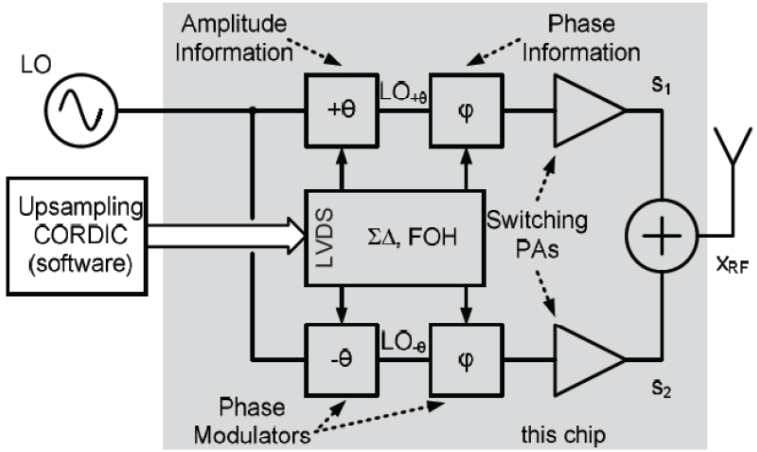


Traditional DCT

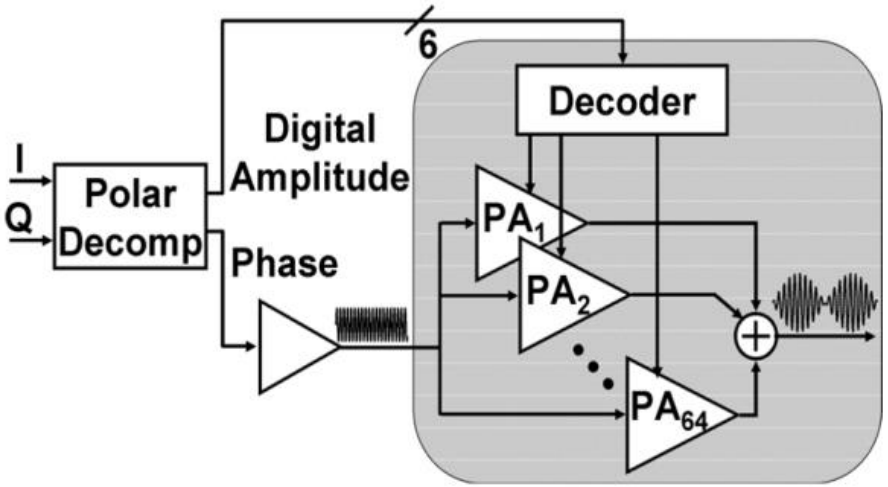
Direct digital IQ Tx

	Conventional Analog Tx	Digital TX
Pros	• High dynamic range • Clean spectrum and low system complexity	•Smaller area & Higher efficiency •Less variation over temp & process •Can support Multi-standard •Benefits from process scaling
Cons	•Area & power does not scale well with process migration	•More non-linear with switching PA •Quantization noise not filtered at BB (rely on over sampling) •Spurs and sampling images

3) Digital transmitter: Polar and out-phasing



Digital outphasing Tx

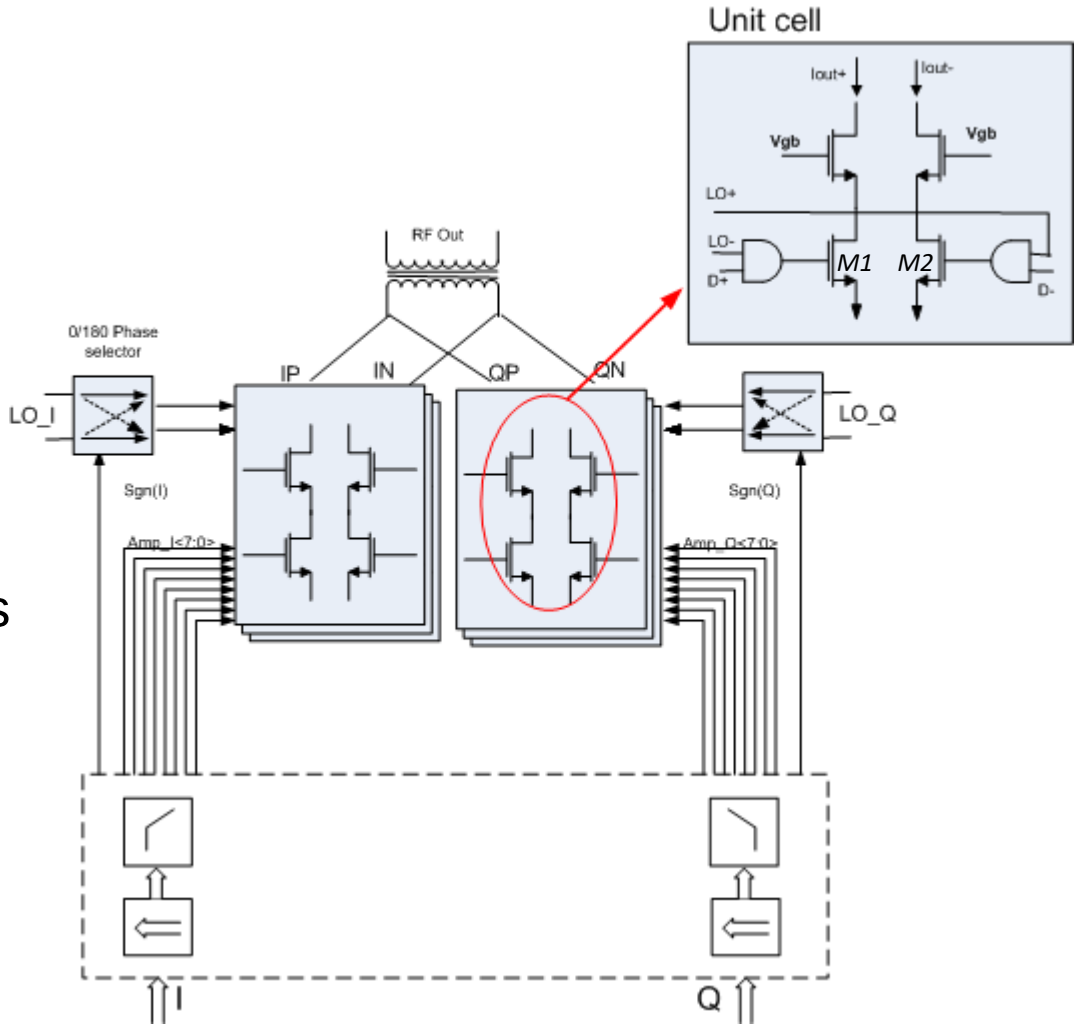


Digital Polar Tx

- Same benefits as digital I/Q
- Several shortcomings as analog counterparts (bandwidth expansion, alignment, efficiency degradation vs backoff, etc)
- Added impairments (spurs, mismatch, DNL/INL, quantization, etc.)
- Verification complexity (CAD issue)

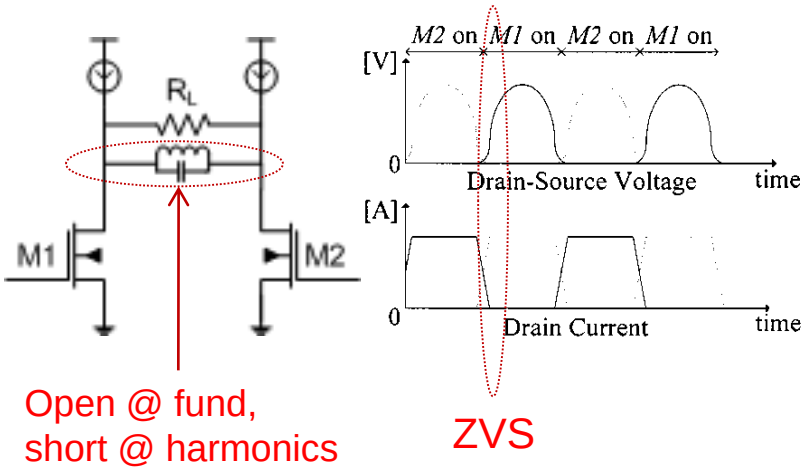
Digital I/Q Tx:

- Practically RF I/Q DACs
- BB digital I/Q signals are first up-sampled (3~5x) to make spectrum for DPD. Then upsampled again (2~3x) to push image out for better rejection (emission)
- Digitized amplitude controls on/off of the PA unit cell
  - Resolution depends on spectrum mask /EVM requirements
- I/Q combination at the output of PAs
- Needs 2x PA area compared to polar



Digital I/Q Tx: switching PA can be used

- Loading termination
  - R_L @ fundamental, short @ higher order harmonics
  - Transistor output cap can be absorbed into the tuning circuit
  - Half-sinusoidal voltage waveform on each single-ended output
- The sinusoidal output waveform enables zero-voltage switching (ZVS)
  - Eliminate discharging dissipation of the output parasitic cap
  - However, it requires a sharp switching edge (i.e. high speed devices) to ensure high efficiency
- Peak voltage: π×VDD
  - Cascode structures and high voltage transistors may be mandatory due to HCI over-stress concern
  - The intermediate nodes are still subject to discharging dissipation, and thus may lower the efficiency

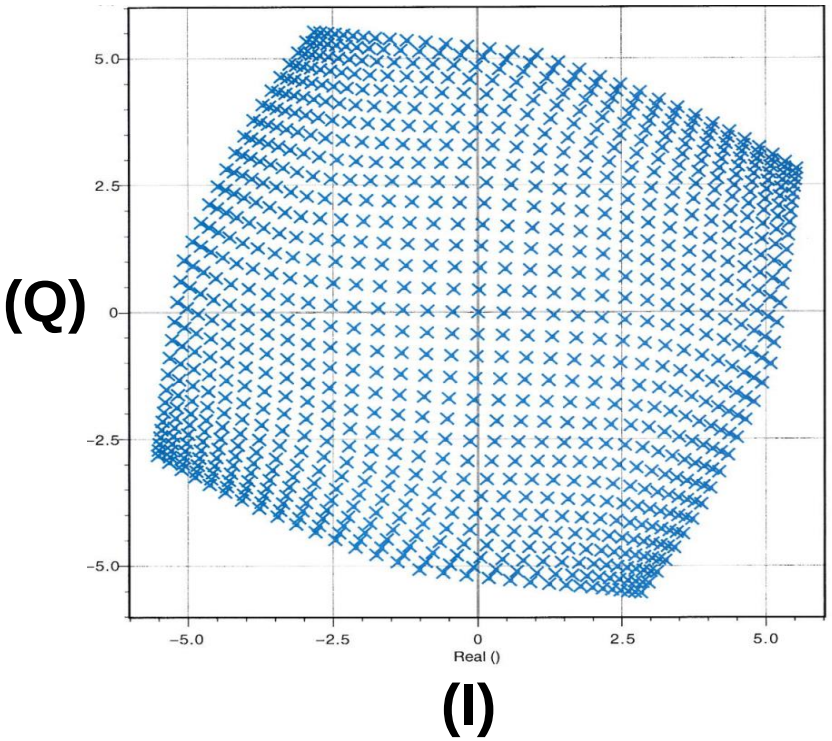


Inverse class-D switching PA

Digital I/Q Tx: Impairments

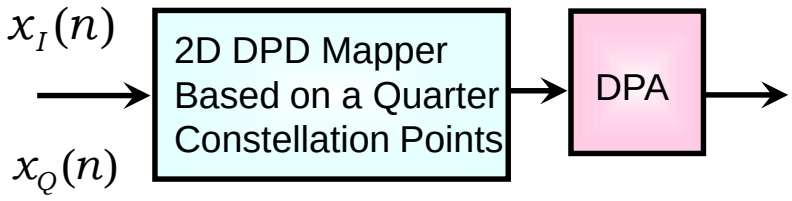
impairments	Affected Performance	Requirements
Quantization noise floor	Noise emission	DAC res.=11~13bits, SDM
IQ interaction	EVM, Mask, noise emission	2-Dimensional DPD
DNL due to mismatch	Noise emission	Good partition bet ween thermo-bits and binary-bits
LO path delay mismatch(Systematic Layout)	Noise emission	Very complicated layout and floor planning
LO buffer delay (Random due to device)	Noise emission	Tradeoff between buffer sizing and power consumption
DPA data bit & sign bit delay mismatch	Noise emission	Very tight timing requirement
High peak voltage	Lifetime	Careful design

Digital I/Q Tx: typical Tx output

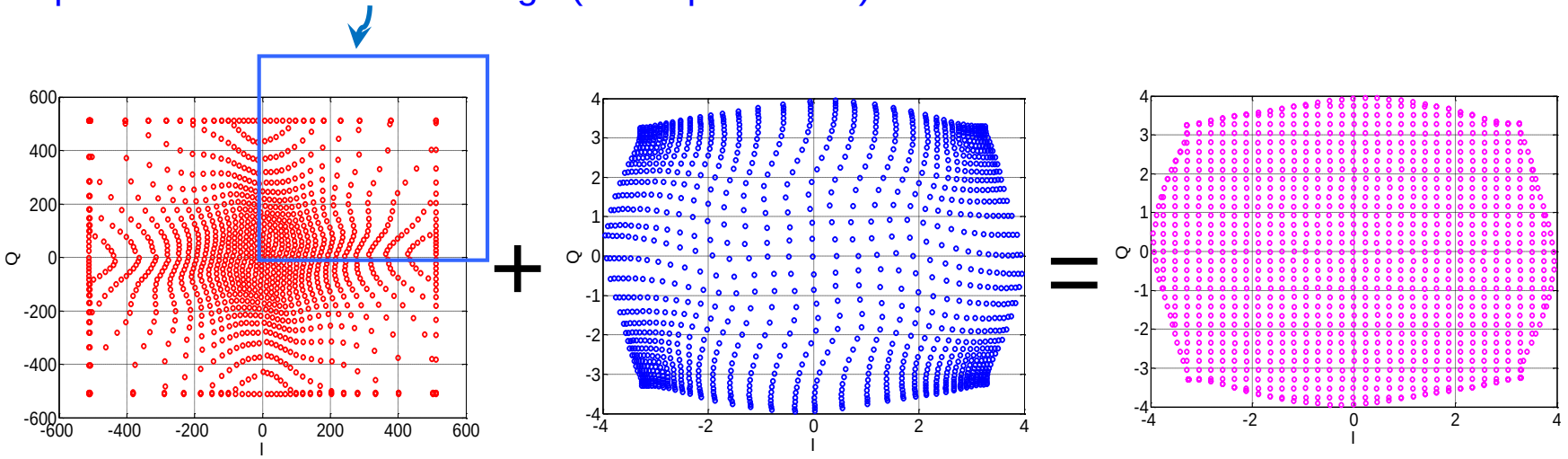


- AM-AM cause compression (dots gets closer at the edges)
- AM-PM cause rotation (warpage) of dots
- Due to I/Q interaction (combiner isolation is finite), the distortion is 2-dimensional needing 2D-DPD to fix

Digital I/Q Tx: DPD

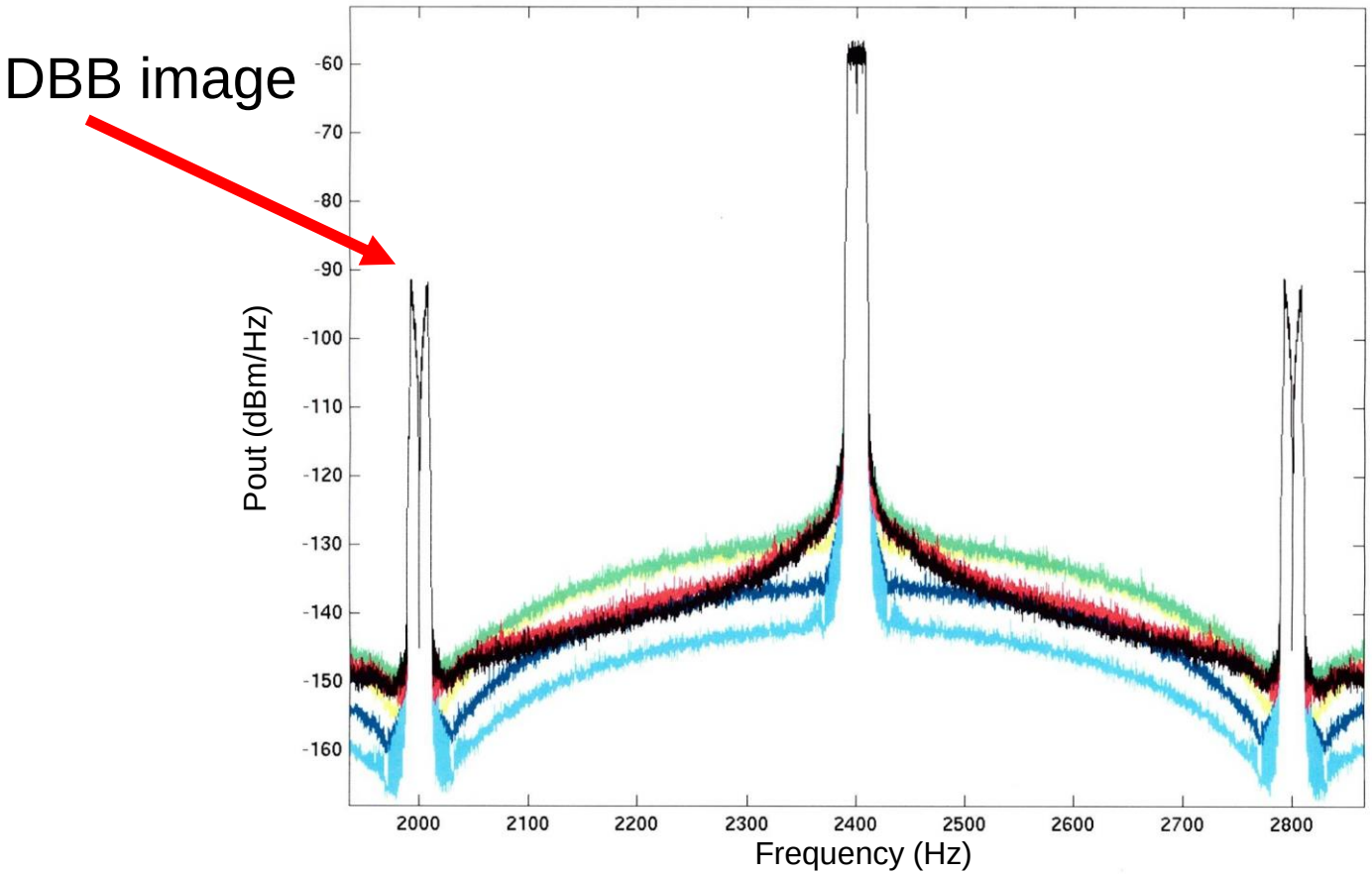


A quarter LUT should be enough (a complex Table).



(a). 2D DPD LUT (b). 2D DPA (c). DPA Output

Digital I/Q Tx: out of band emission



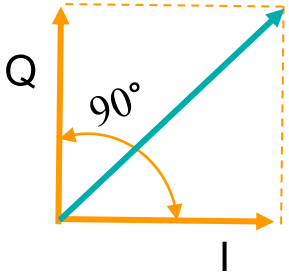
- Out of band emission is usually dominated by DPA quantization noise and DNL (mismatch). The different plots above are for different number of bits and different arrangement between thermometer code bits and binary bits
- Other contributors are LO phase noise and emission spurs such as digital-baseband image (blue/red curves)

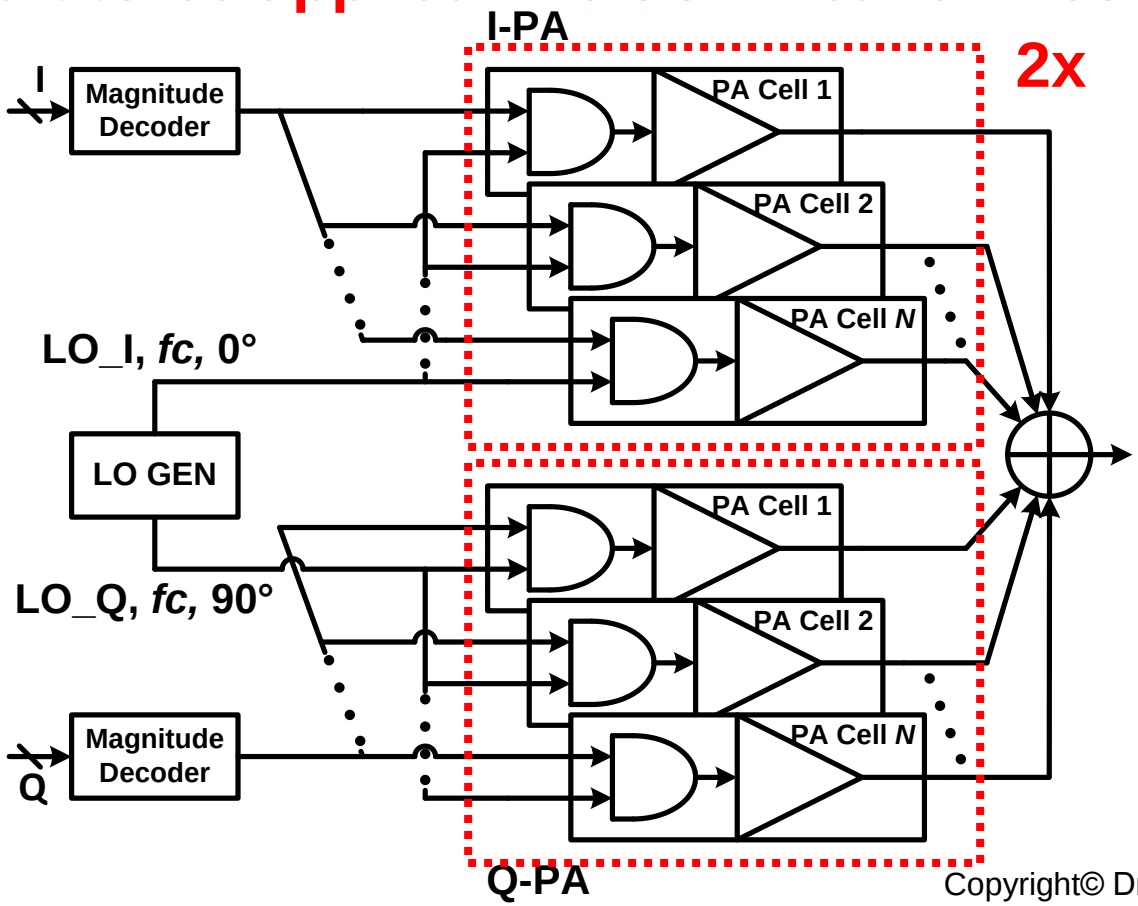
Digital I/Q, separate banks for I&Q

☺ **No Sig BW Expansion**

☹ **Double PA Cell Size→ Parasitics↑ → Efficiency↓**

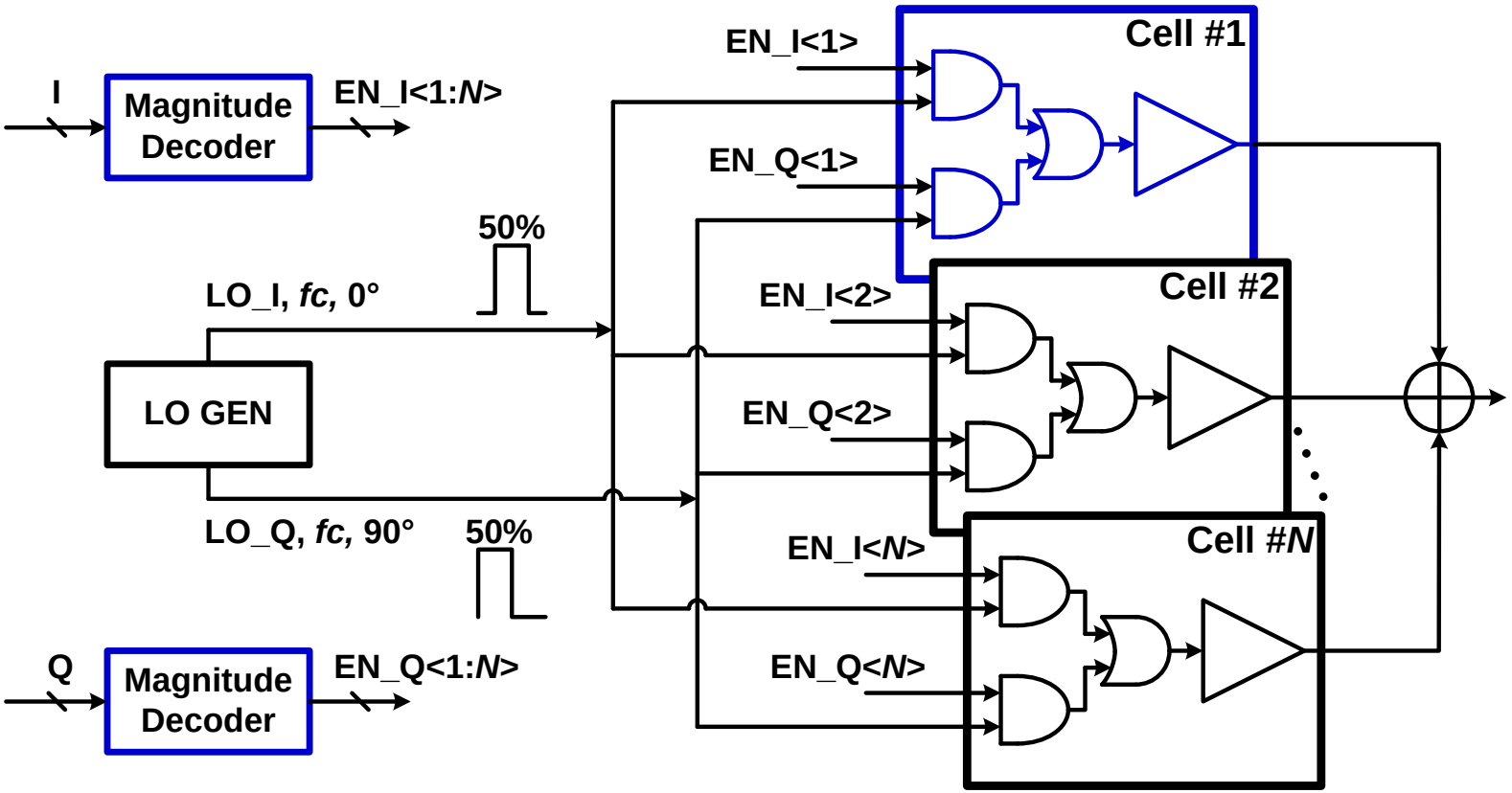
☞ **Difficult to be applied in 5.5GHz-band in 55nm CMOS**





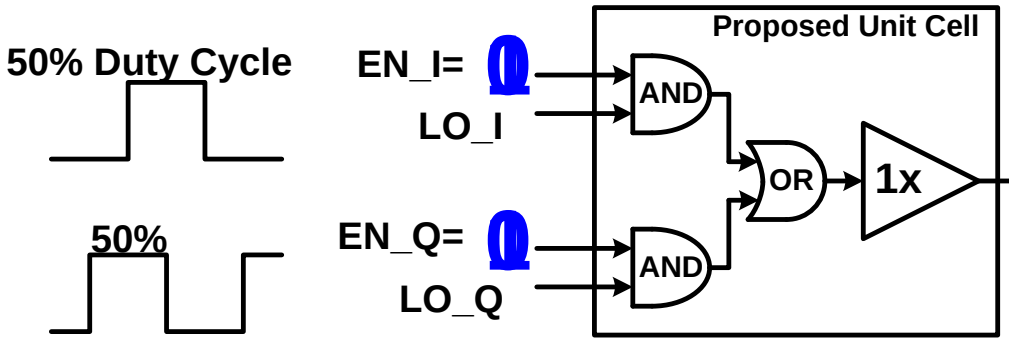
Modified Architecture: I/Q Sharing

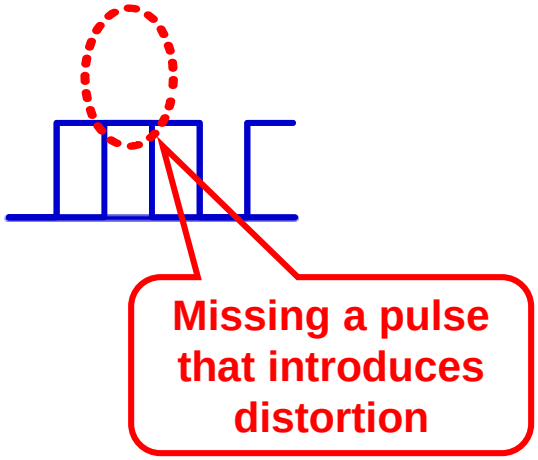
- ☺ No Sig BW Expansion
- ☺ Half PA Size compared to Conventional I/Q
- ☺ 50% duty cycle LO signals



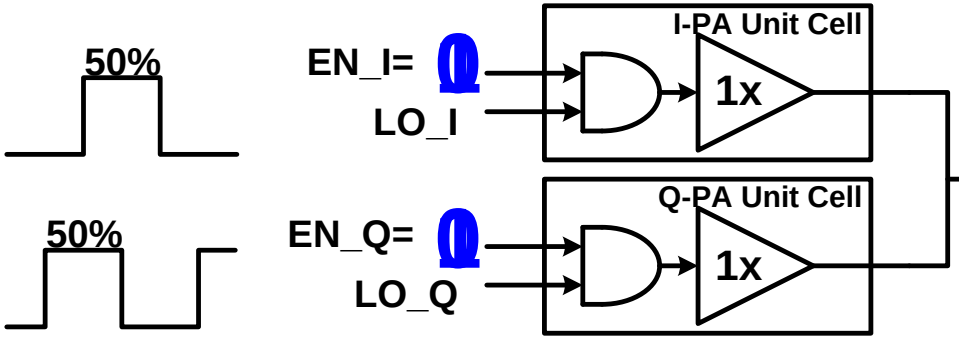
DPA Core: I/Q OR-Combination

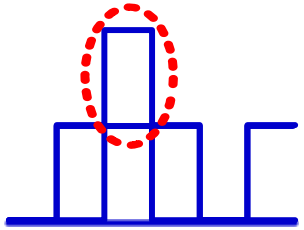
Proposed OR-combination [1]





Conventional RF-combination [2]

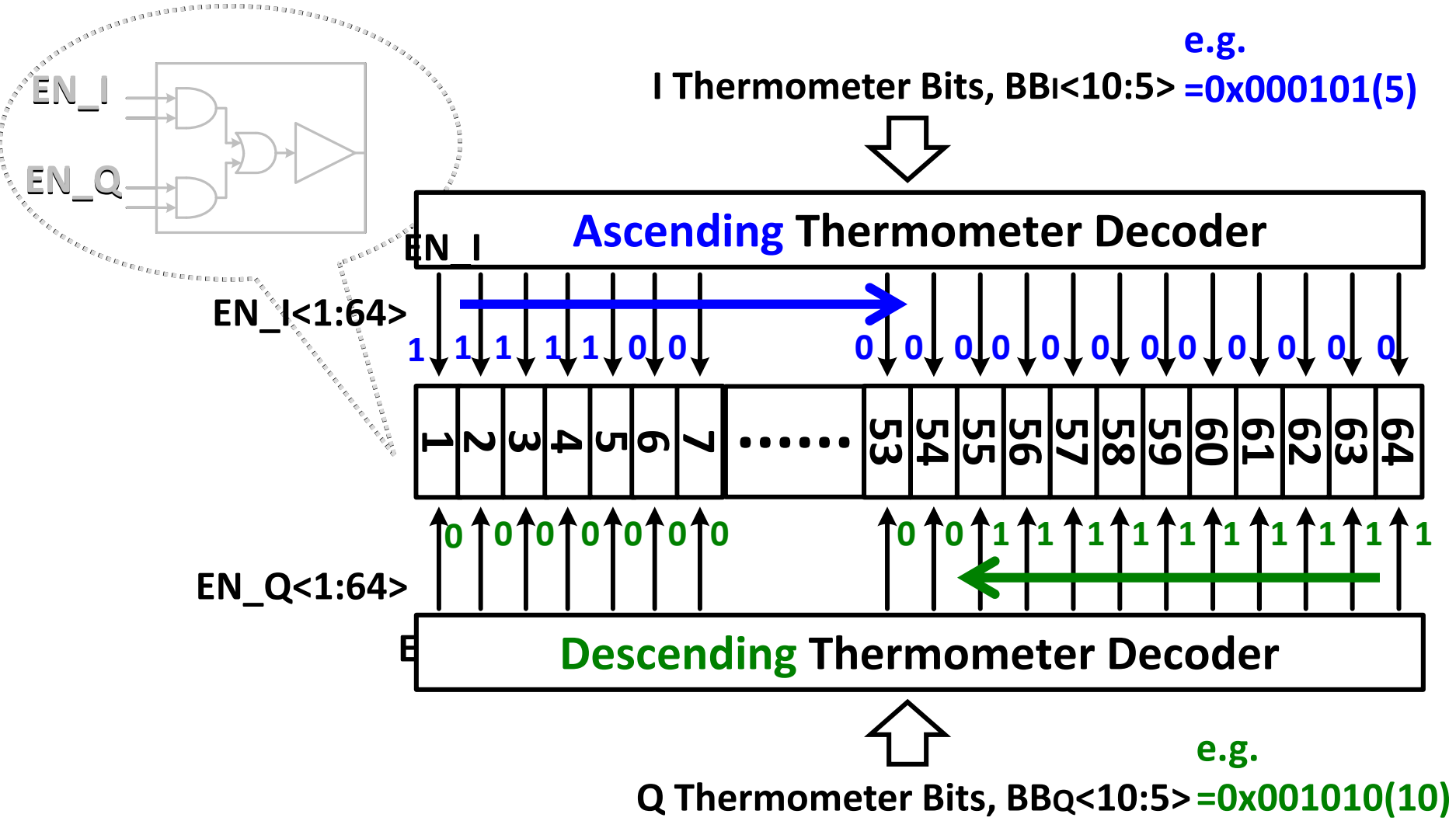




EN_I	EN_Q	Iiq-shared = Iconv ?
0	0	☺
0	1	☺
1	0	☺
1	1	☹

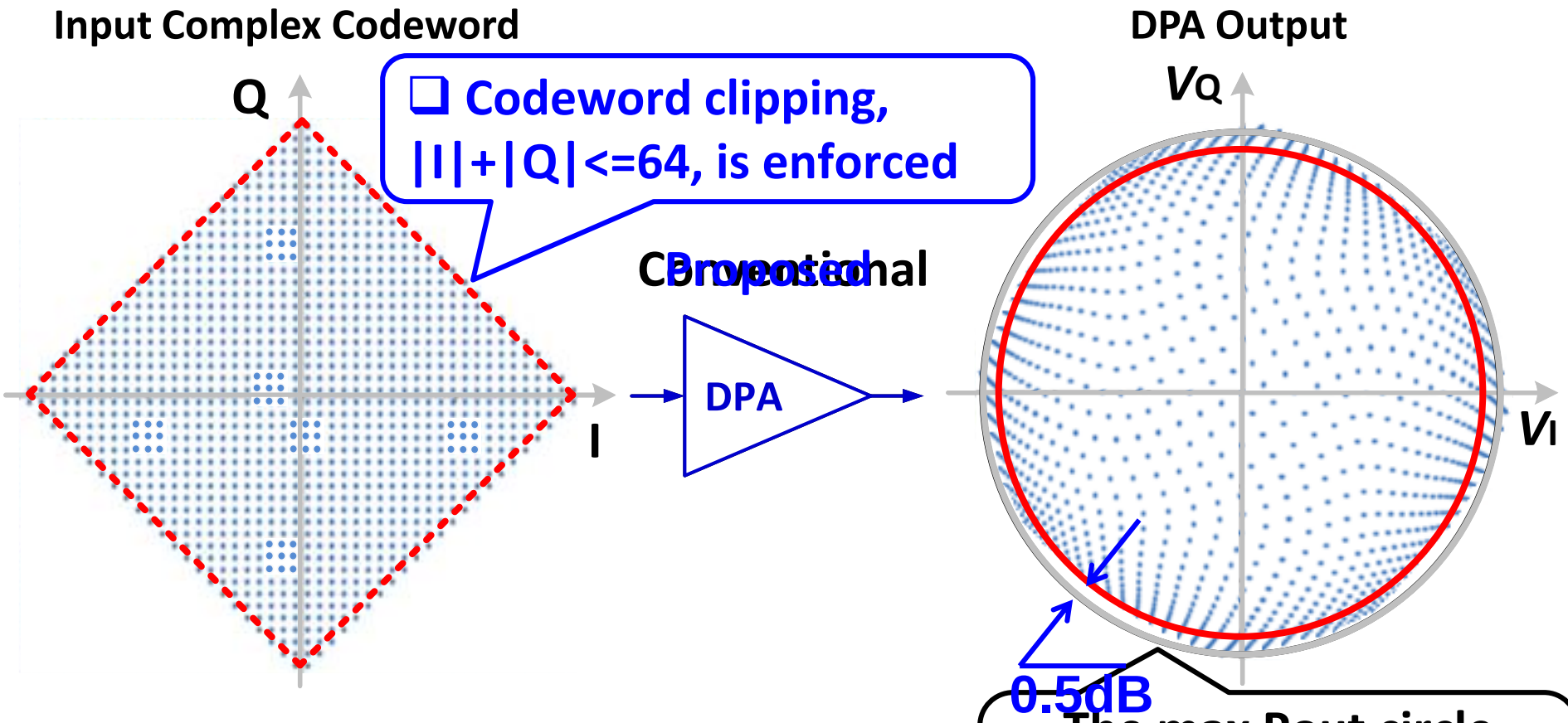
- **Half cell size**
- Output distorted when I/Q overlaps (EN_I=EN_Q="1")

I/Q Complementary Decoding



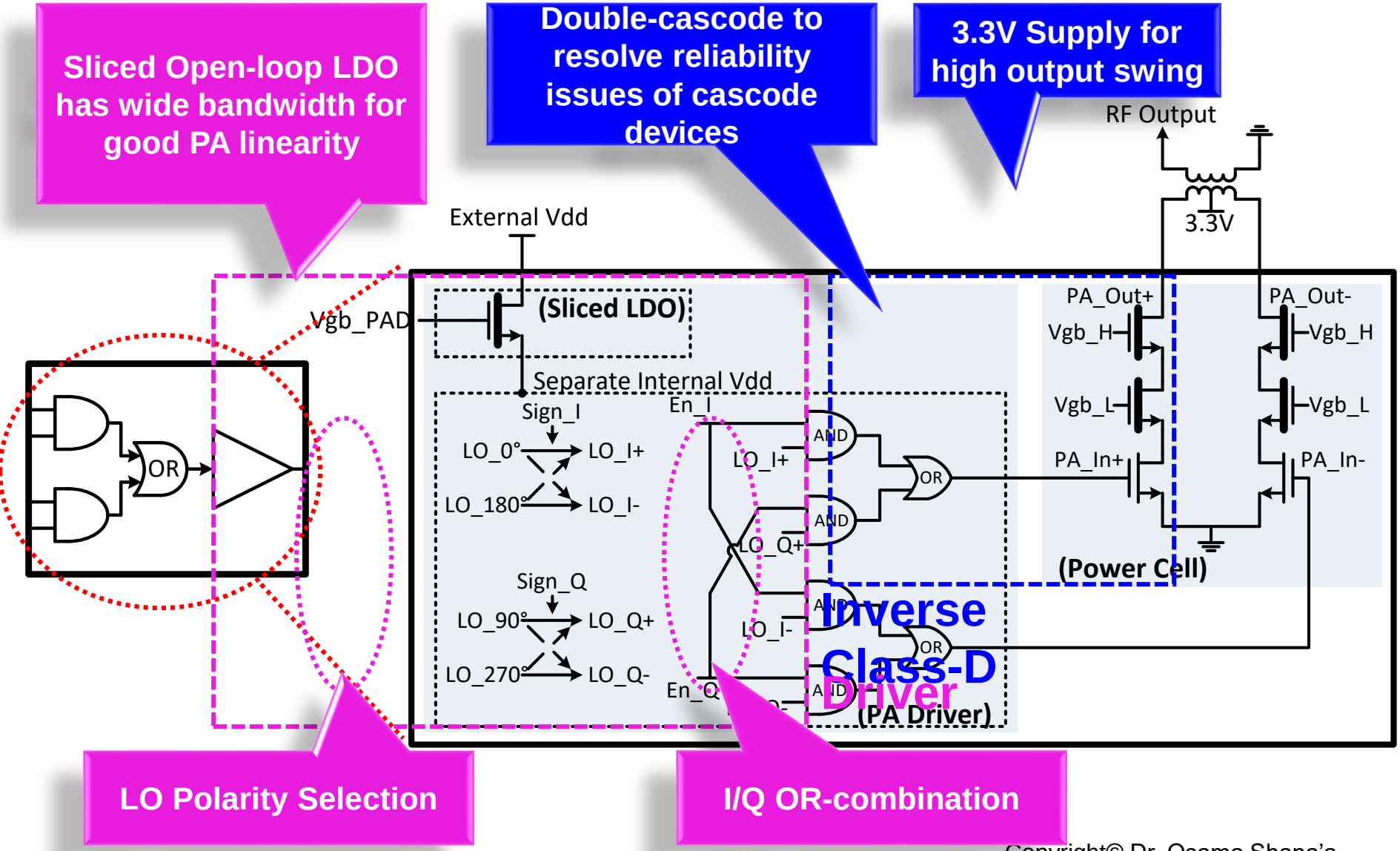
❑ **I/Q overlap is prevented for input levels** $|I|+|Q|<=64$

Diamond Profile Mapping

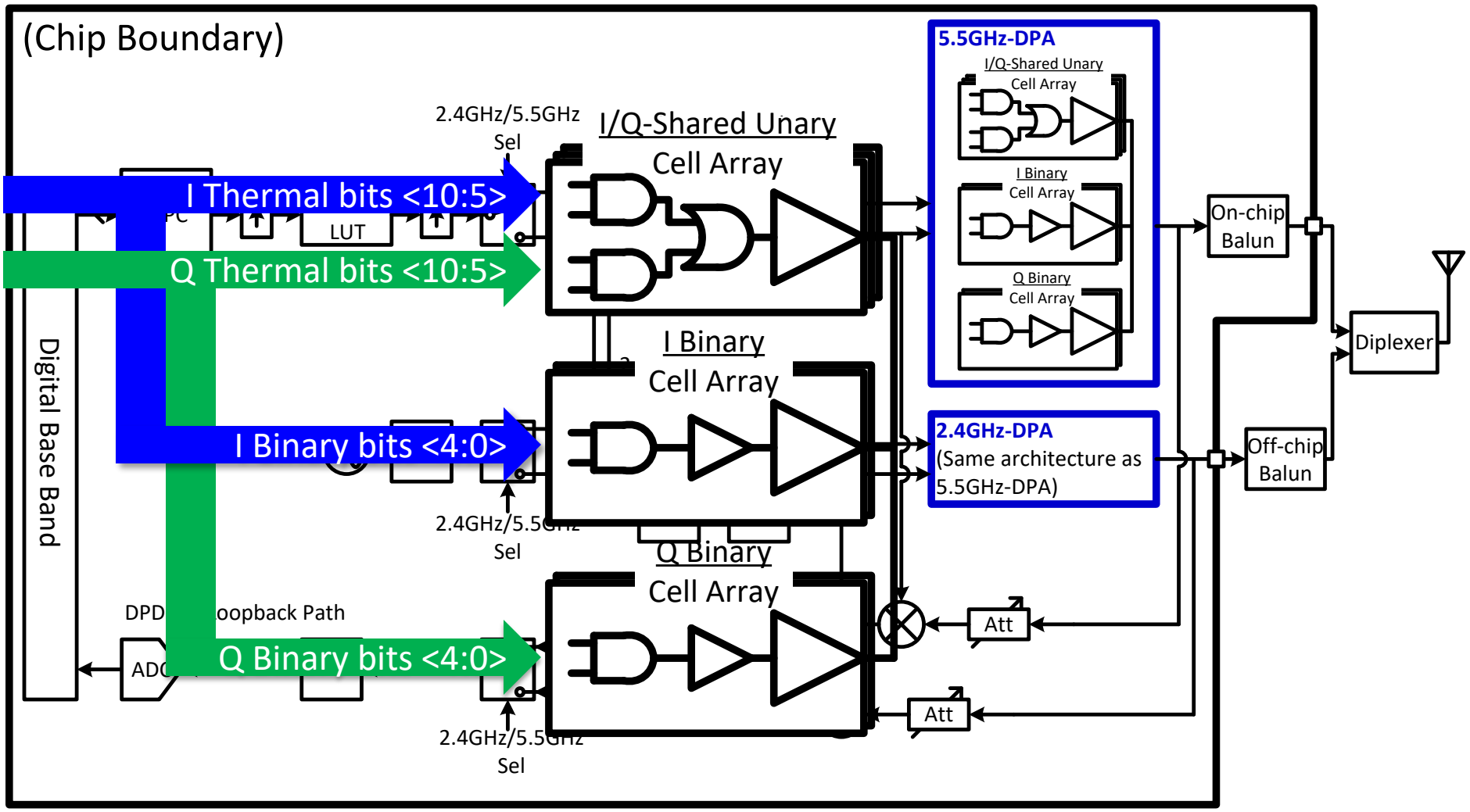


❑ The proposed DPA (**half PA size** compared to conventional) can achieve **almost the same OFDM output power** (0.5dB degradation).

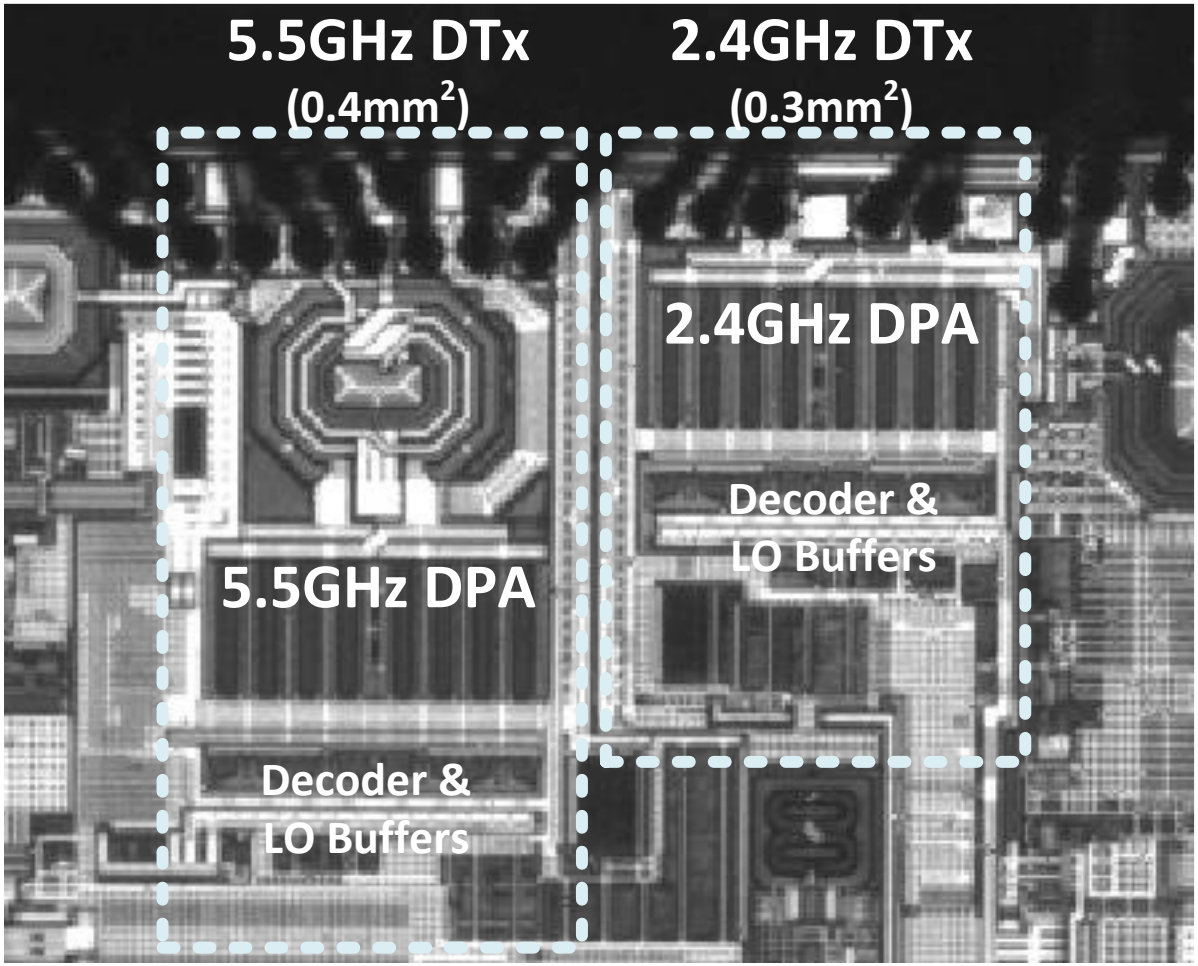
PA Unit Cell Implementation



Fully Integrated Dual-band DTX

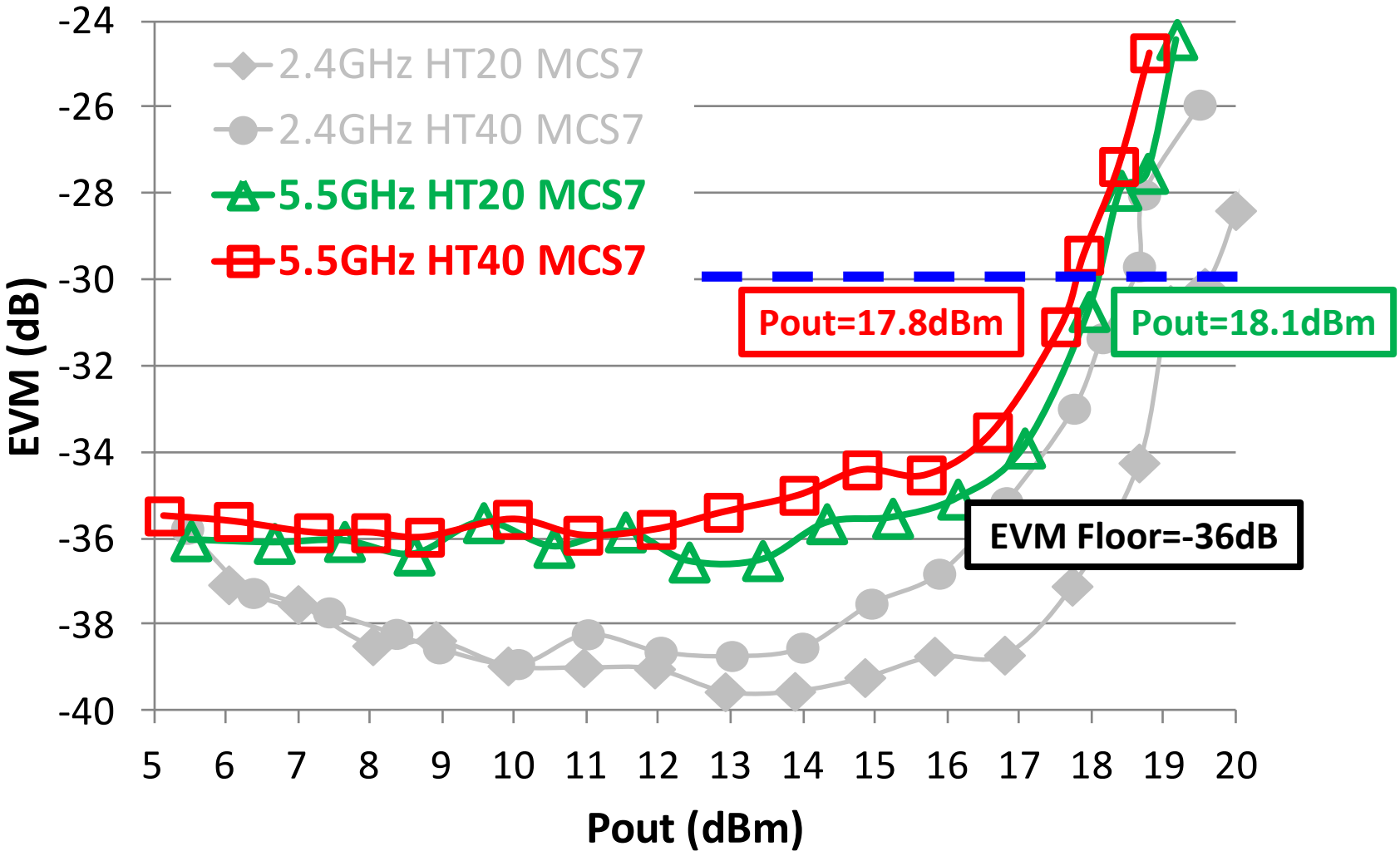


Die Photo



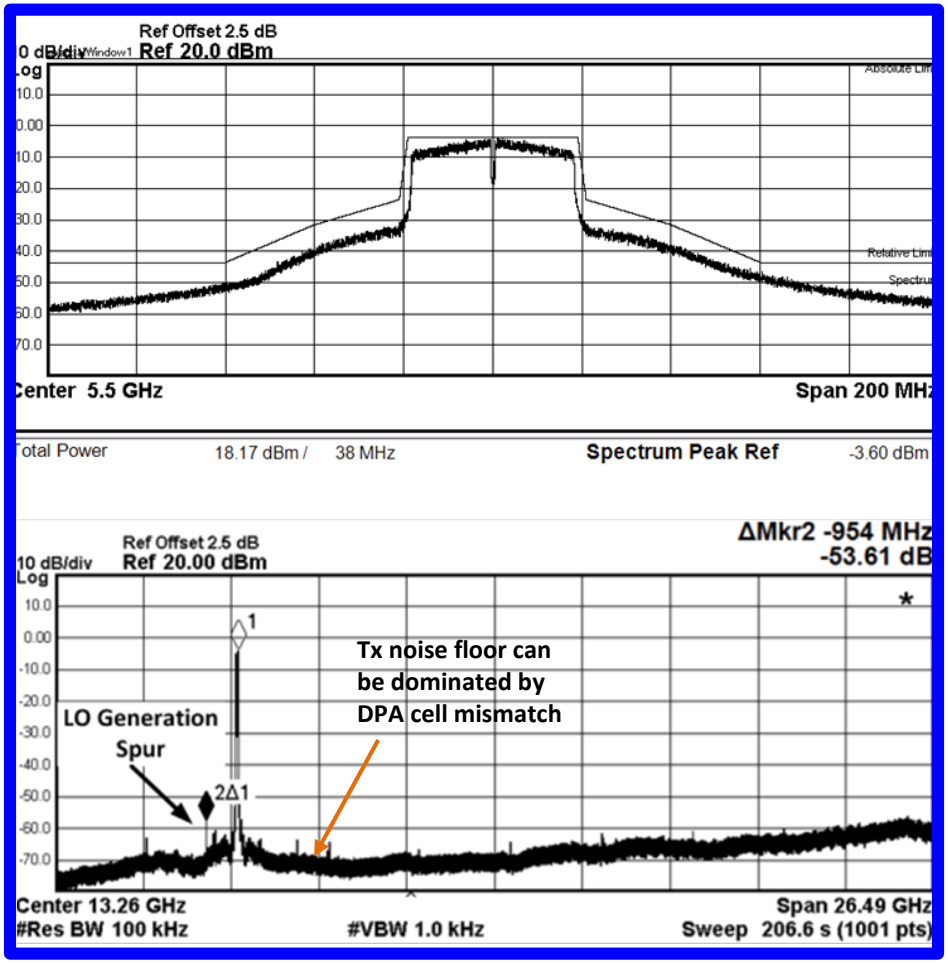
- 40nm digital CMOS
- 68-pin 7mm x 7mm QFN package
- Die Area:
  - 5.5GHz DTX: 0.4 mm^2
  - 2.4GHz DTX: 0.3 mm^2
- Part of a 2x2 Dual-band WiFi transceiver SOC

Measured EVM vs Pout (5.5GHz 11n)

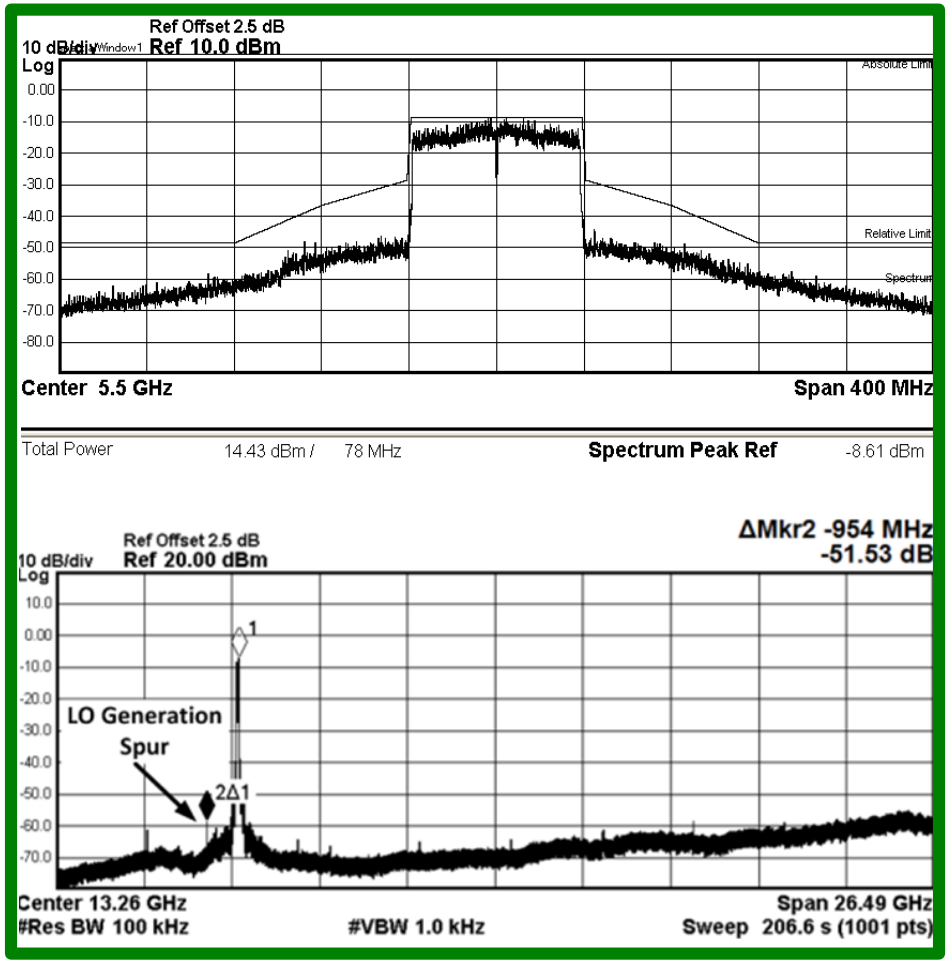


Measured Spectrum (5.5GHz)

11n HT40 MCS7, Pout = 18.2dBm



11ac VHT80 MCS9, Pout = 14.4 dBm



- Measurement shows IEEE PSD mask compliant with 3dB margin

Performance table

Reference			This Work [1] ISSCC 2016
Technology			40nm CMOS
Supported WiFi Standard			a/b/g/n
DTX Architecture			Dig. IQ w/ I/Q digital-OR combination and diamond-shape DPA profile
SOC			Yes
PA Supply Voltage			3.3V
5.5GHz	TX Die Area		0.4mm^2
	Psat		25.5dBm
	HT20 MCS7	Pout	18.1dBm@EVM=-30
	HT40 MCS7		17.8dBm@EVM=-30
	VHT80 MCS9		14.3dBm@EVM=-32
	DPA Efficiency		14.1%@7.5dB-backoff #
2.4GHz	TX Die Area		0.3mm^2
	Psat		27.0dBm
	HT20 MCS7	Pout	19.5dBm@EVM=-30
	HT40 MCS7		18.6dBm@EVM=-30
	DPA Efficiency		14.5%@8dB-backoff #

- Loss of balun and integrated T/R switch, but not diplexer, is included in all measurements of all bands
- Efficiency is good (2X compared to analog DCT) but is still not great

References:

[1] Zhiming Deng, Eric Lu, Edris Rostami, Dai Sieh, Dimitris Papadopoulos, Bryan Huang, Ray Chen, Hua Wang, WH. Hsu, CH. Wu, and Osama Shanaa, "A Dual-Band Digital WiFi 802.11 a/b/g/n Transmitter SoC With Digital I/Q Combining and Diamond Profile Mapping For Compact Die Area and Improved Efficiency in 40nm CMOS," *ISSCC Dig. Tech. papers*, pp 172-173, Feb 2016

[2] Chao Lu, Hua Wang, CH Peng, Ankush Goel, SangWon Son, Paul Liang, Ali Ninjejad, HC Hwang, George Chien, "A 24.7dBm all-digital RF transmitter for multimode broadband applications in 40nm CMOS," *ISSCC Dig. Tech. papers*, pp 332-333, Feb 2013

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