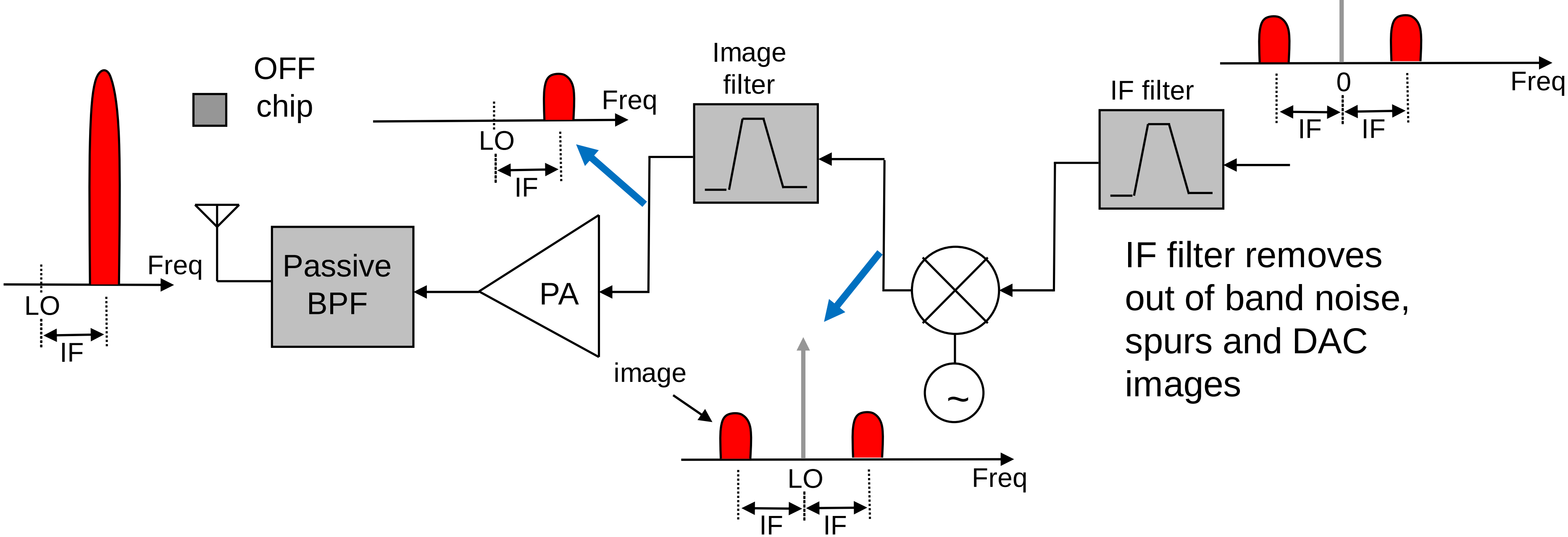
Narrow-band Transmitter Radio Architectures

- **Double-conversion (Superhetrodyne)**
- **Direct-conversion (DCT)**
- **References**

1) The Superhetrodyne Architecture:



IF filter removes out of band noise, spurs and DAC images

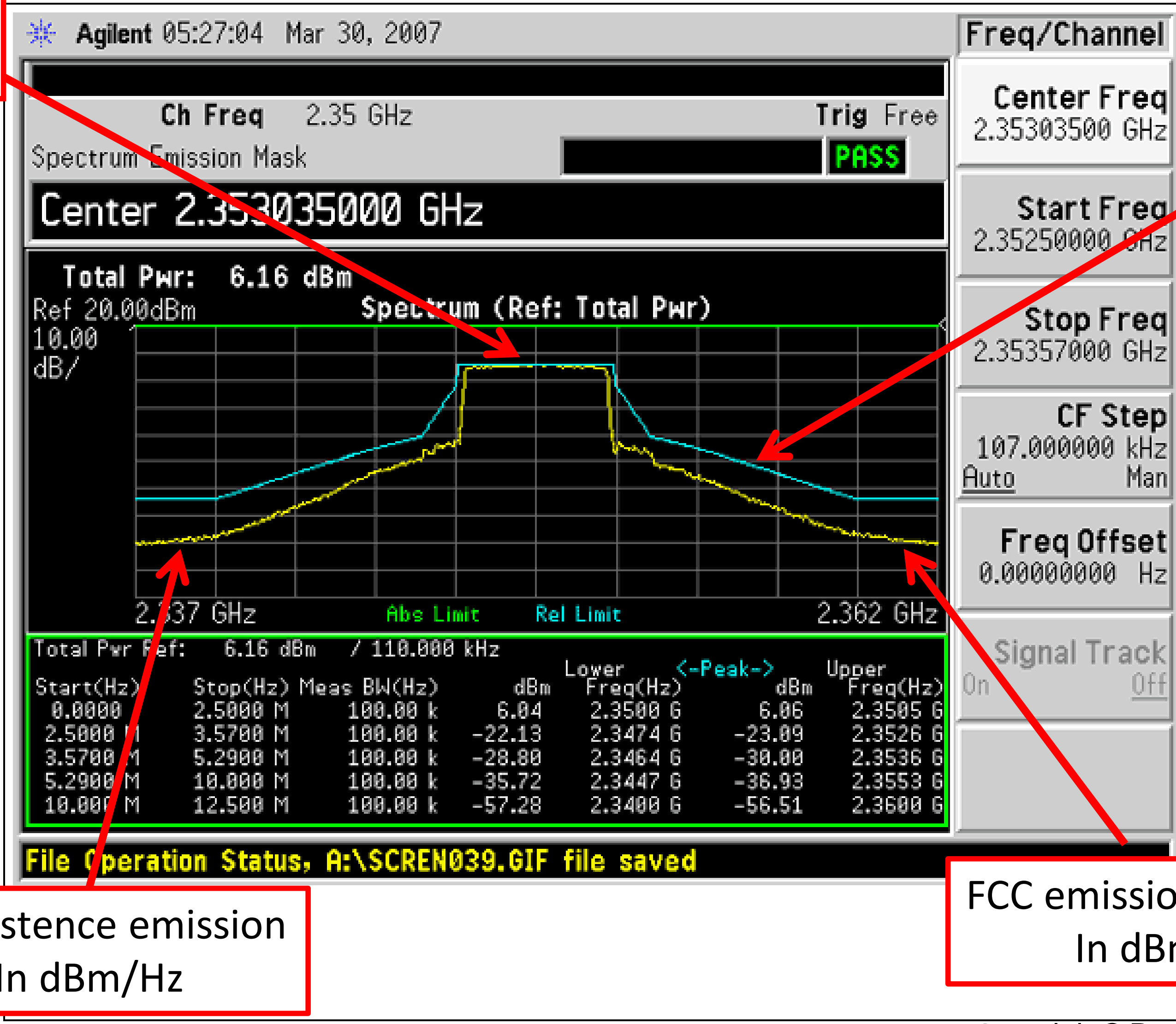
Just like Rx superhet:

- IF frequency is carefully chosen as compromise between image rejection and filter Q
- Robust design but is bulky and needs several off-chip components
- same issues of Rx superhet applies here for Tx as well

What does a transmitter need to achieve?

In band EVM in dBc

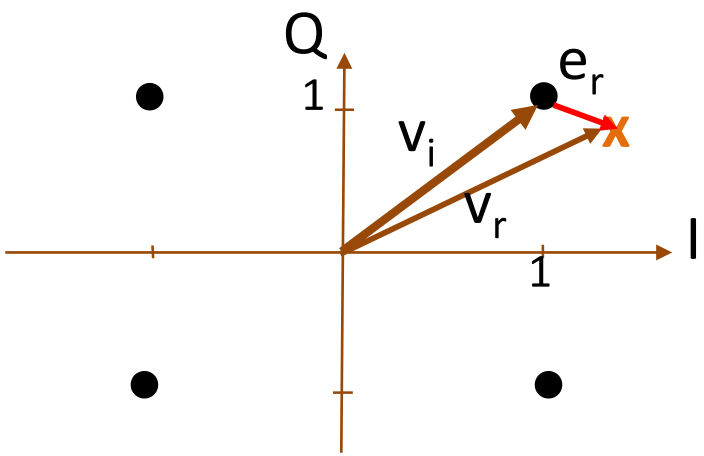
Emission mask in dBr

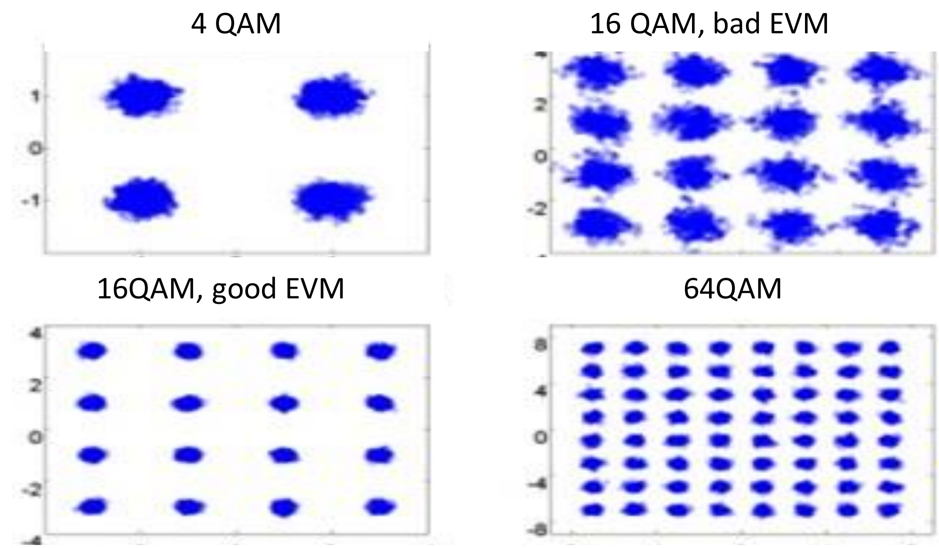


Co-existence emission In dBm/Hz

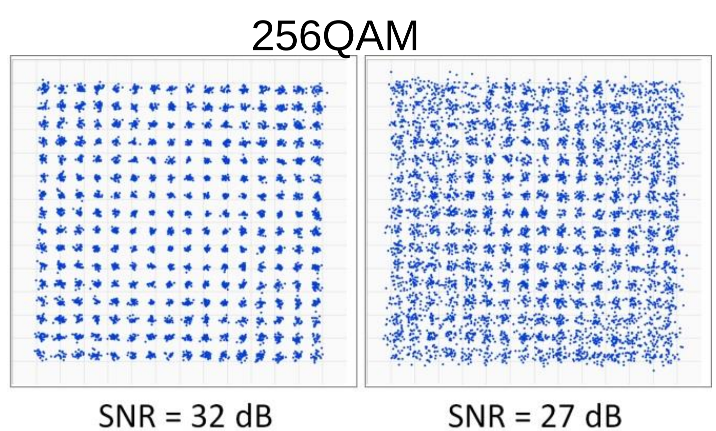
FCC emission regulation In dBm/MHz

Tx EVM in a picture:

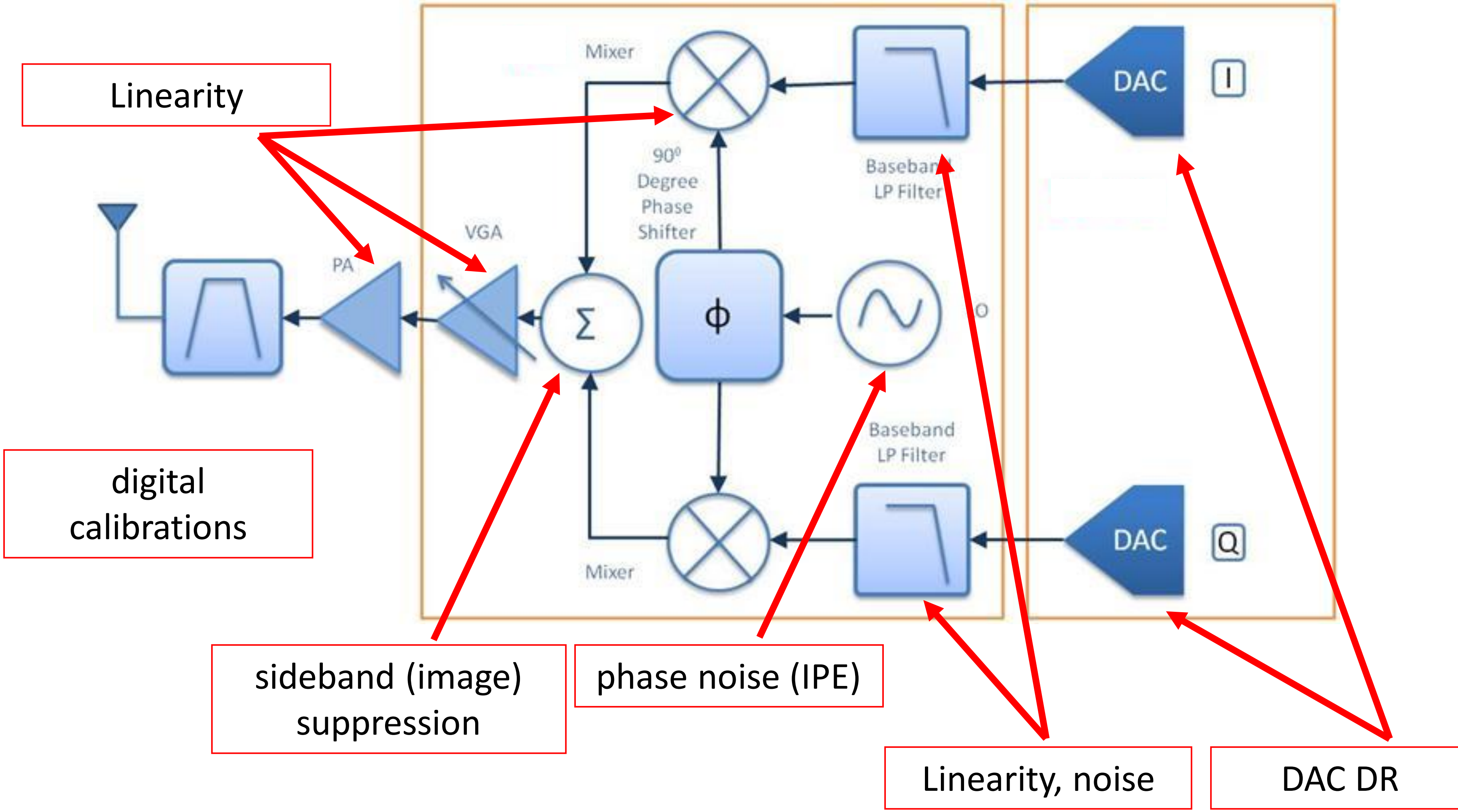




- EVM is a measure of constellation quality
- As constellation points get closer, better EVM is required for low BER

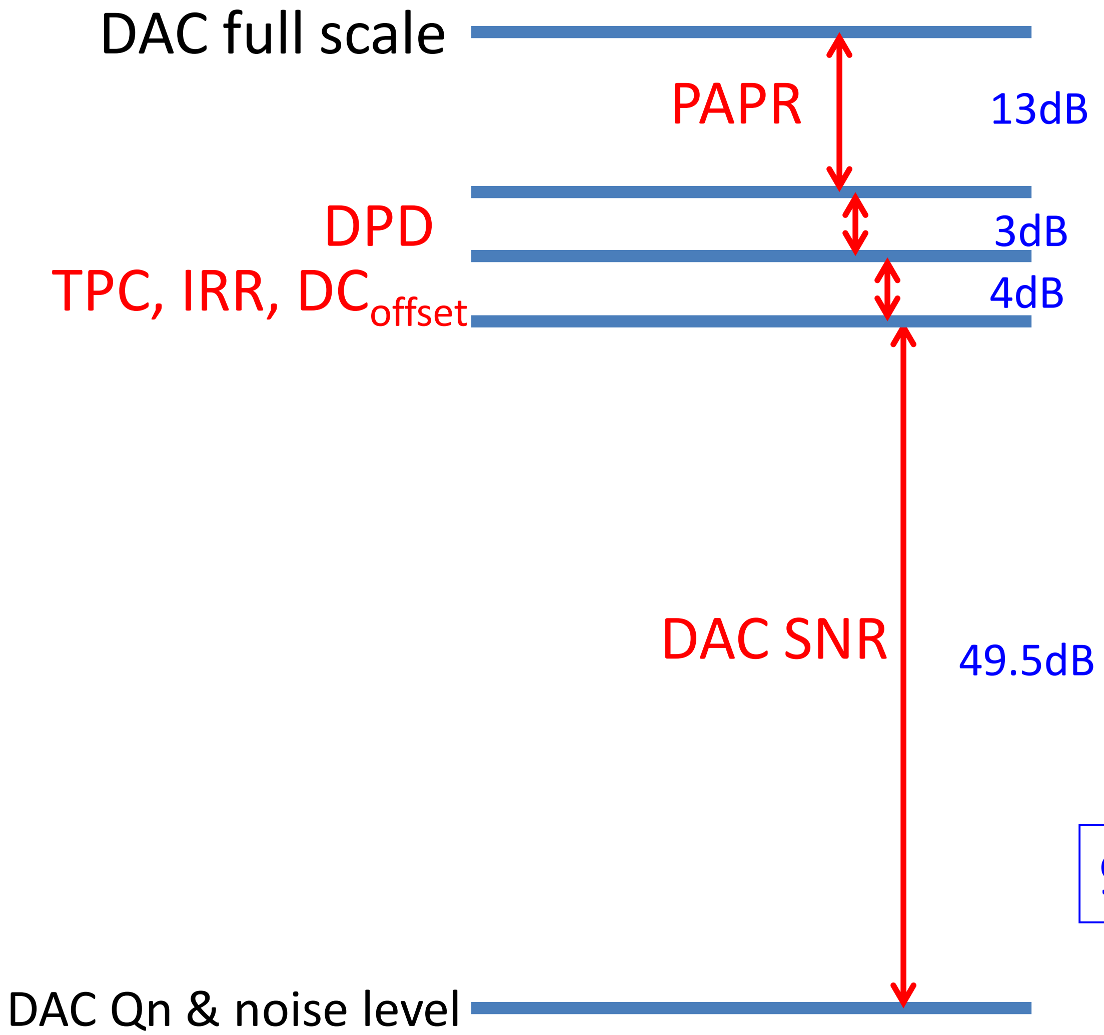


Direct Up-conversion Tx (DCT):



→ Tx efficiency is of great importance

Impairments of DCT: DAC DR



Example: Tx EVM target -38dB
→ DAC noise is >10dB lower
→ 49.5dBc

9.5b DAC with 12x OSR

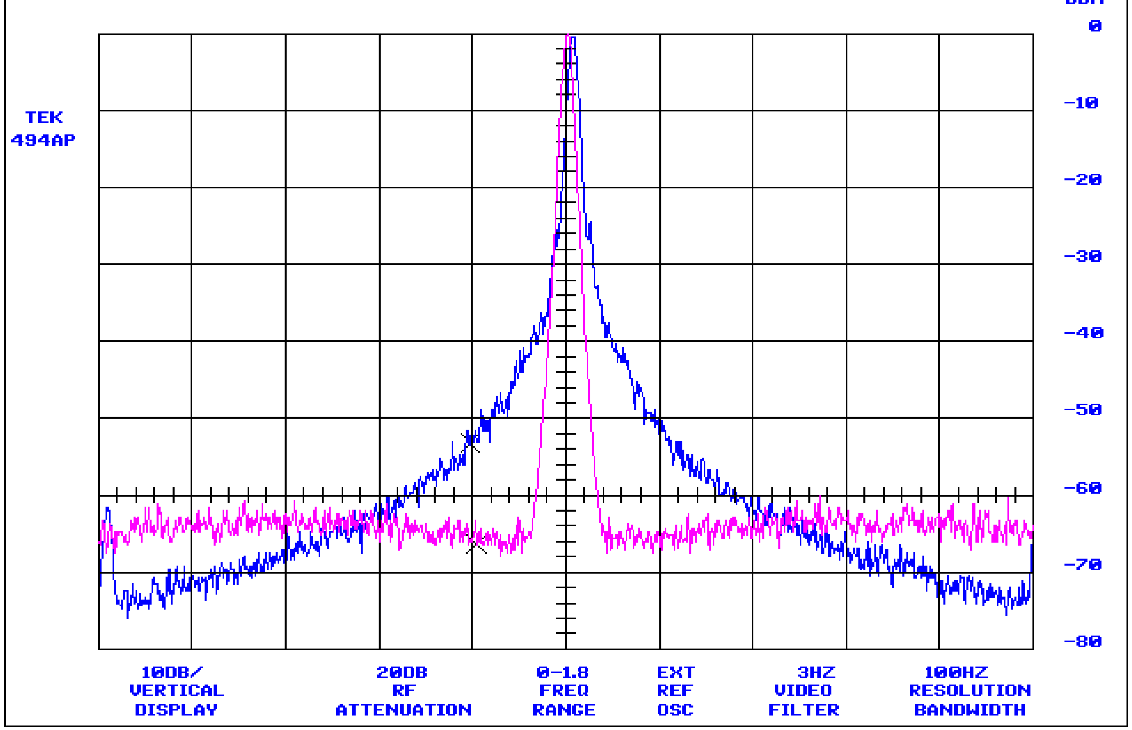
Impairments of DCT: LO phase noise (IPE)

$$m(t)\cos(\omega_0 t + \varphi(t) + \phi(t))$$

IPE = ϕ *rad*

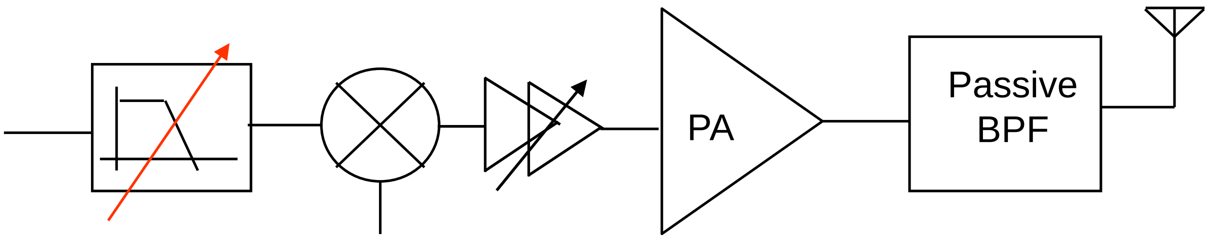
SNR = -20log ϕ *dB*

|EVM|= SNR – 3dB for WiFi



- For -38dB EVM target, LO EVM budget is 10dB better or -48dB → IPE of only **0.16°** at 5.9GHz for WiFi A-band
- Synthesizer design becomes tougher as EVM target gets more stringent

Impairments of DCT: linearity (IM3 and IM5)



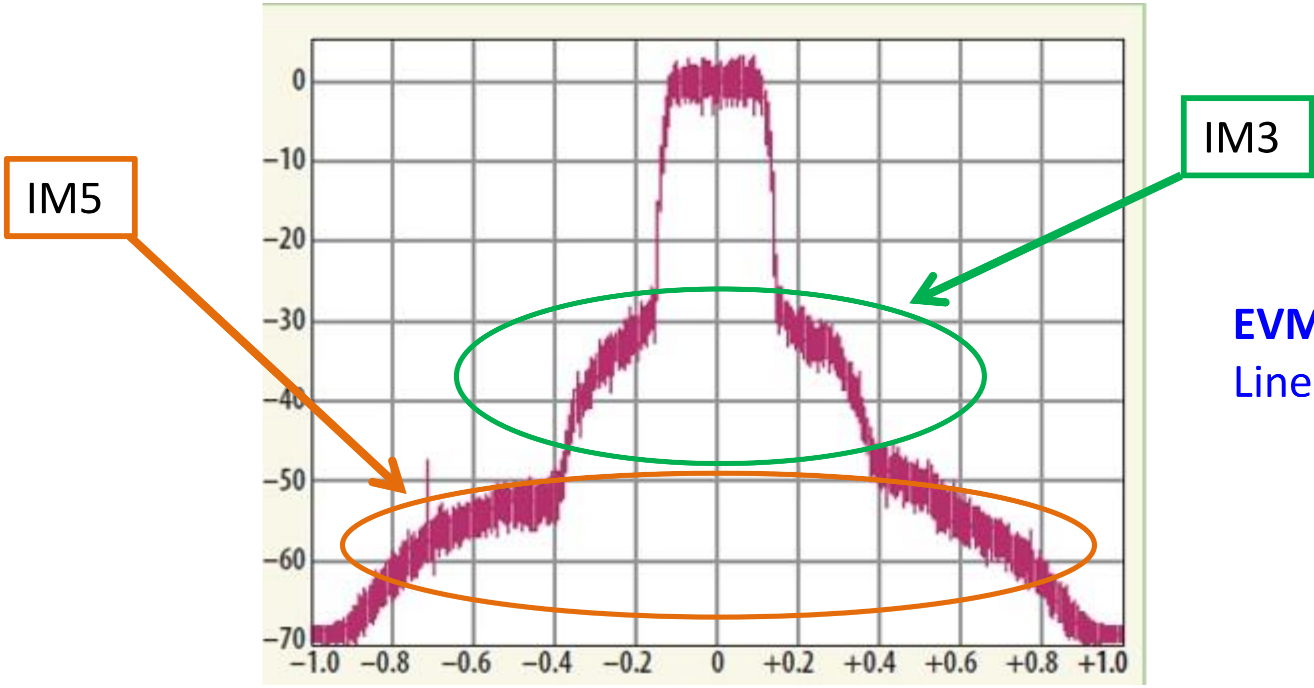
$$S(t) = m(t)cos(\omega t + \varphi(t))$$

If Tx signal passes through a weakly none-linear block

$$\alpha_3 S(t)^3 = \alpha_3[m(t)cos(\omega t + \varphi(t))]^3 = \alpha_3 m(t)^3 cos(\omega t + \varphi(t)) + \dots$$
$$\alpha_5 S(t)^5 = \alpha_5[m(t)cos(\omega t + \varphi(t))]^5 = \alpha_5 m(t)^5 cos(\omega t + \varphi(t)) + \dots$$

- 3rd and 5th order nonelinearity result in an in-band distortion (called IM3 and IM5). The IM3 distortion has 3x BW compared to desired signal (5th has 5x). This is called spectrum re-growth.
- IM3, IM5 affect both in-band EVM/SNR and out-of band emission

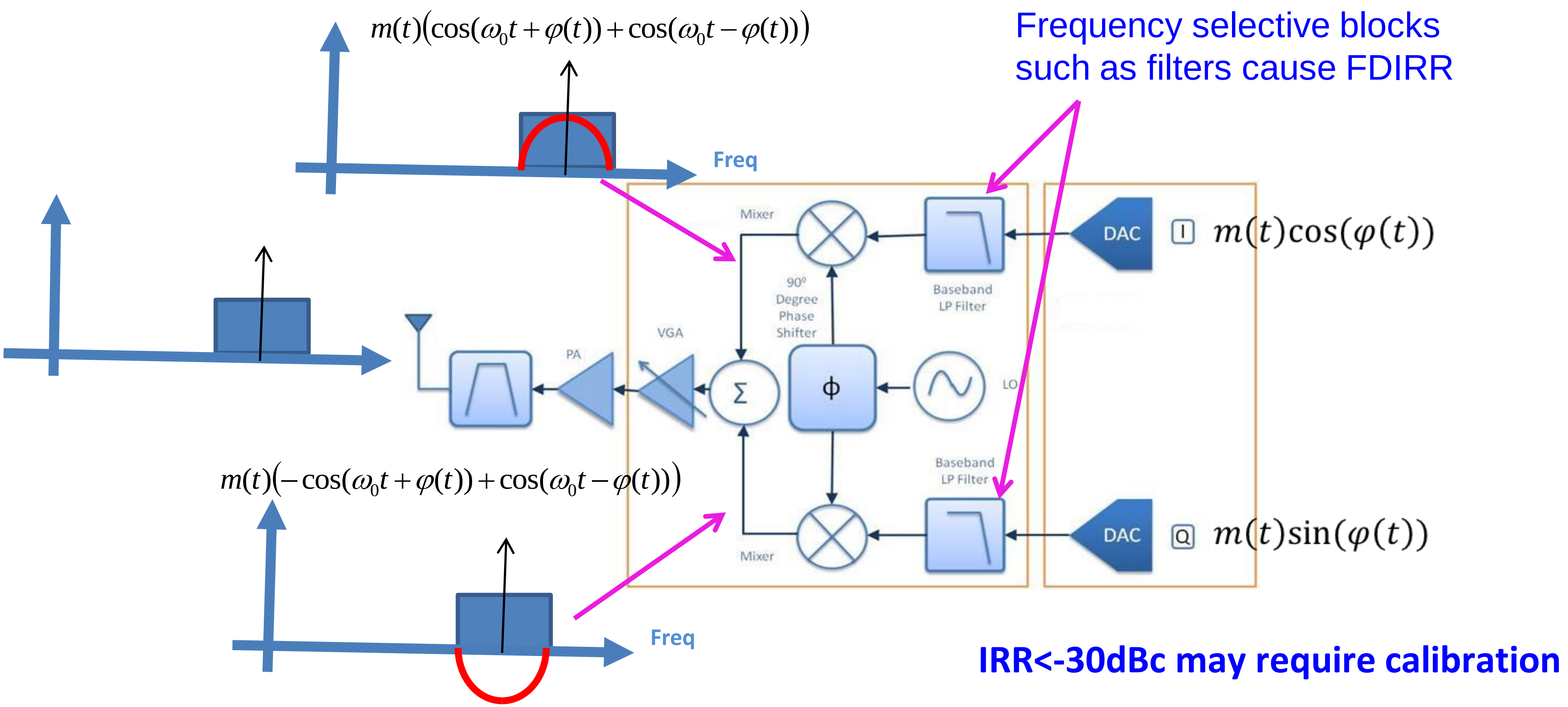
Impairments of DCT: linearity (IM3 and IM5)



EVM budget (exc PA):
Linearity: -48dB

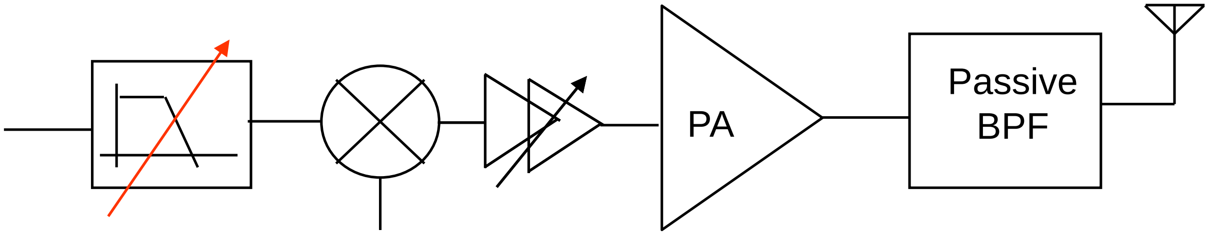
- IM3/IM5 in-band distortion is budgeted as 10dB below target Tx EVM (excluding PA)
- Usually IM3/IM5 of entire Tx is dominated by PA (so other Tx blocks are designed with IM3/IM5 at least 10dB better than that of PA)

Impairments of DCT: Image (side-band) suppression



- I/Q gain or phase imbalance causes image distortion degrading EVM (static IRR or Frequency-dependent FIRR).
- FDIRR is frequency offset (channel bandwidth) dependent and is caused by blocks like baseband filters. FI-IRR is usually caused by LO and mixer

Impairments of DCT: noise



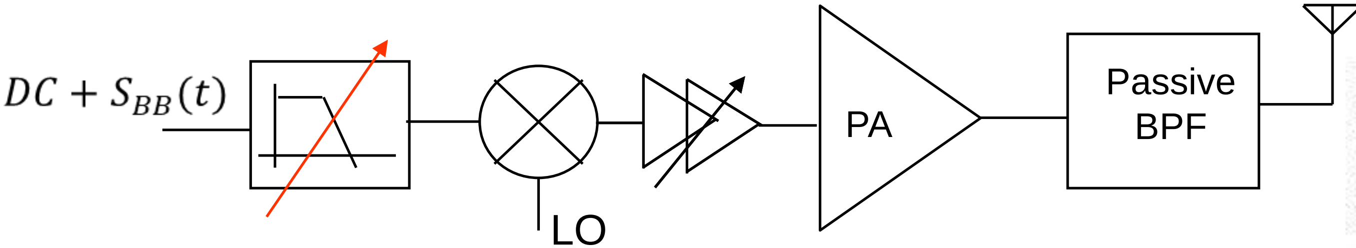
Pout= $S(t) * G_{filter} * G_{mix} * G_{PGA} * G_{PA} * L_{BPF}$

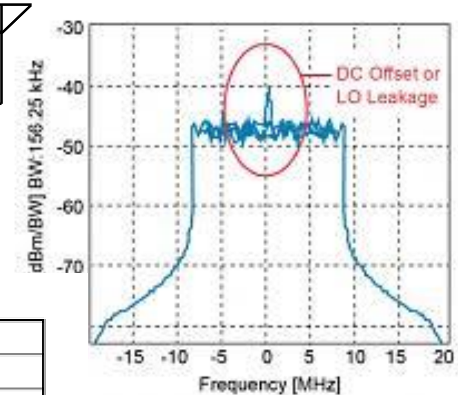
The noise at the output, however can be written as:

$$\overline{n_{out}^2} = \overline{n_{filter}^2} * G_{filter} * G_{mix} * G_{PGA} * G_{PA} * L_{BPF} + \overline{n_{mix}^2} * G_{mix} * G_{PGA} * G_{PA} * L_{BPF} + \overline{n_{PGA}^2} * G_{PGA} * G_{PA} * L_{BPF} + \overline{n_{PA}^2} * G_{PA} * L_{BPF}$$

- In-band noise is dominated by earlier stages of the chain such as the LPF.
- Out of band emission is also affected by noise (again dominated usually by LPF

Impairments of DCT: LO feedthrough (LOFT)

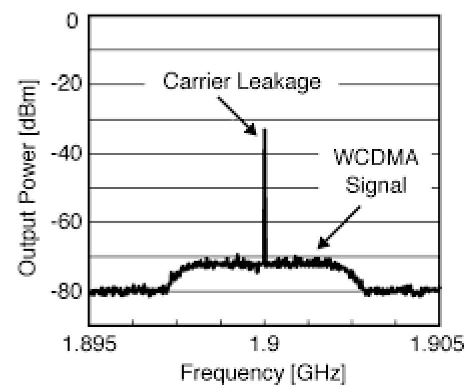




$$\mathrm{BB} = DC + S_{BB}(t)$$

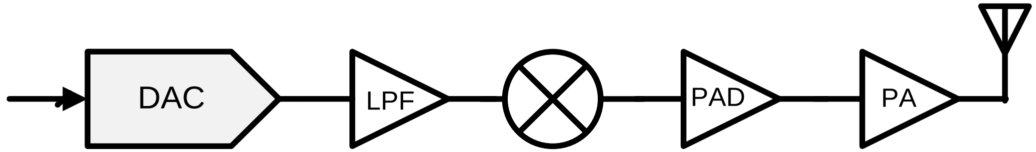
After mixing with LO:

$$S_{out}(t) = DC * \cos\big(\omega(t)\big) + S_{RF}(t)$$



- DC offset at baseband results in LO leakage at RF
- LO leakage can cause emission issue and confuse receiver AGC.
- Need to suppress LO leakage by DC-offset calibration
- Most systems require <-25dBc of LO suppression (needs calibration)
- LOFT changes as baseband gain changes (this is why BB AGC is limited to <~3dB)

Budgeting example of a DCT Tx: WiFi 11ax example

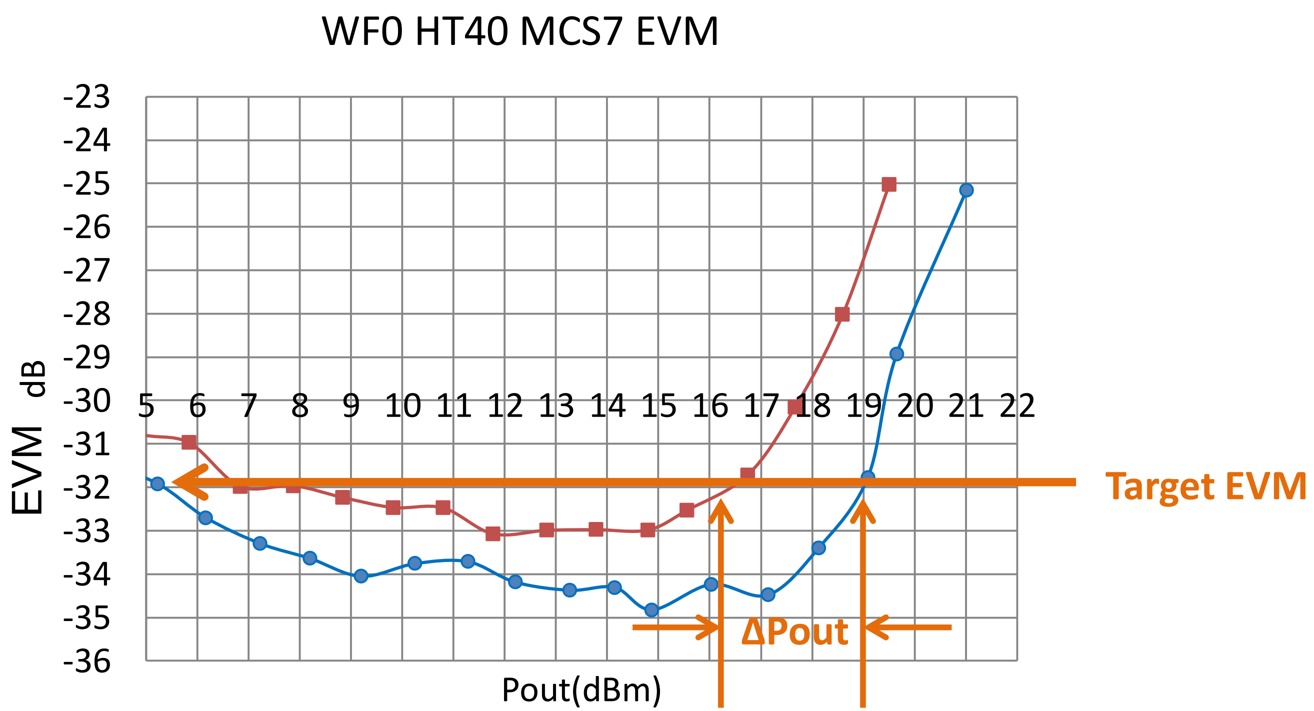


EVM calculator	11ac(MCS11)	Unit
EVM Requirement (160MHz)	**-35**	dB
DFE+DAC SNR	-49.5	dB
Calibrated FD+FI IRR	-48.0	dB
Integrated Phase Noise	-46.0	dB
TX Noise	-45.0	dB
TX Linearity (IM3) – Exc PA	-45.0	dB
other	-45.0	dB
Total EVM	**-38**	**dB**

** allocated -38dB EVM for PA-alone so total transmit EVM hits the -35dB target (illustration purpose)*

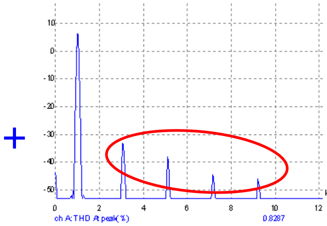
- With so many impairments, in order to achieve a target EVM of -35dB, each impairment needs to have EVM contribution -45dB or better!

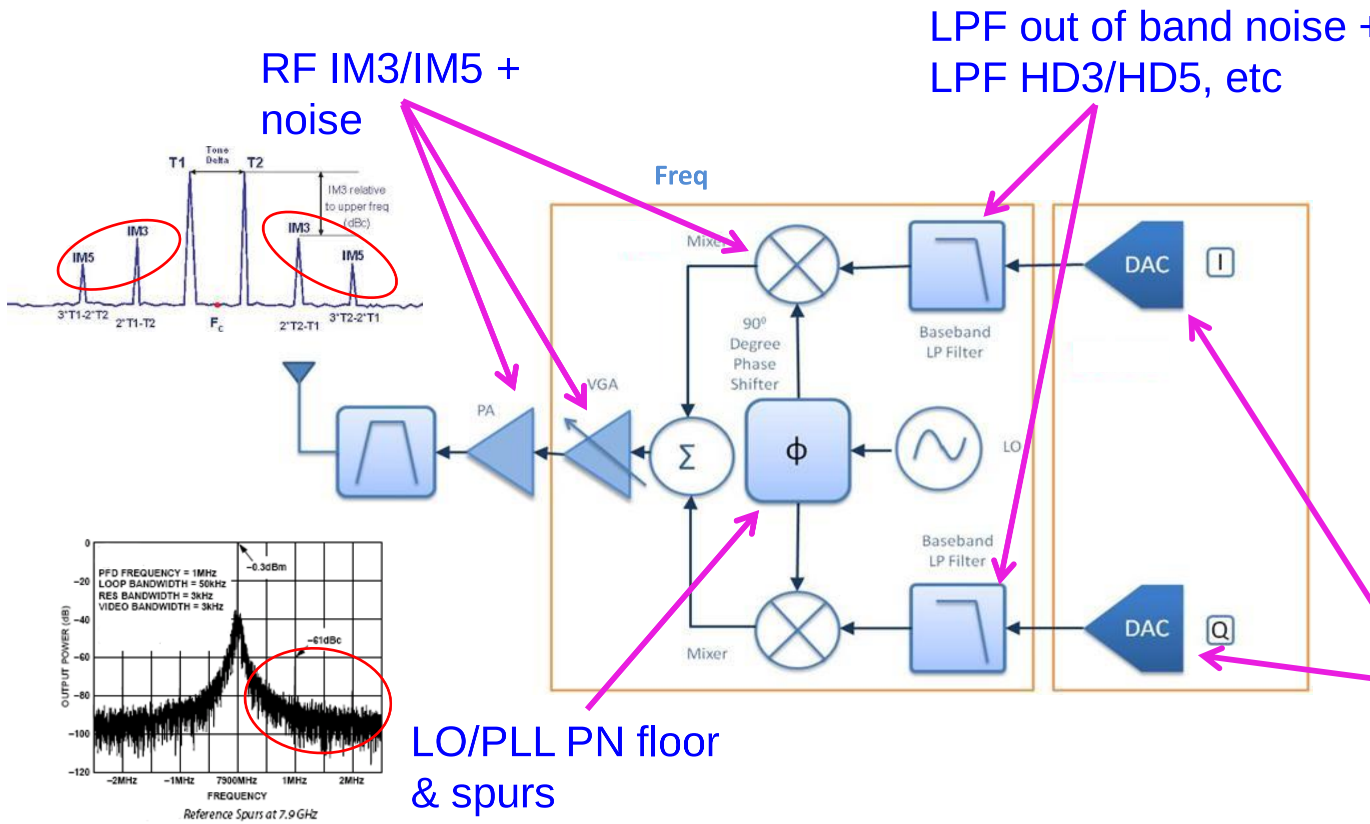
Tx EVM vs Pout: WiFi 11ax example

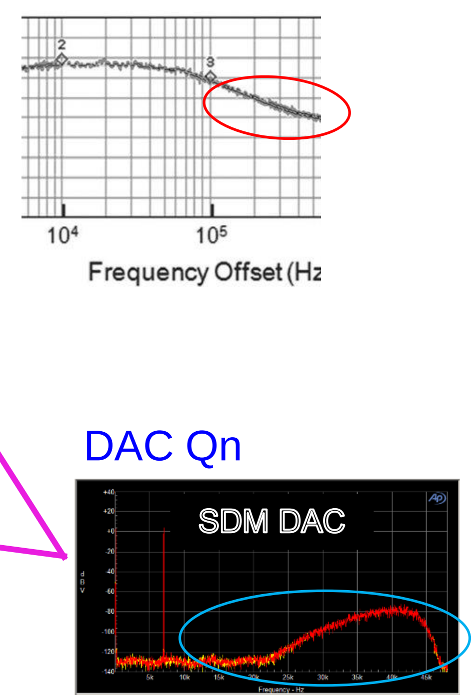


- better EVM floor results in higher Pout at the target EVM
- EVM floor is set by signal-independent impairments (LO IPE, IRR, DAC-Qn, etc.)

Impairments of DCT: out of band emission







- LPF out of band noise and HD usually dominates emission due to Tx gain
- RF IM3 and IM5 are usually the second most dominant (PA mainly)
- LO/PLL PN floor and DAC Qn usually come last (depends on your budgeting)
- There is one more “nasty” impairment that will be discussed next

Impairments of DCT: out of band emission, CIM3

What is CIM3 (Counter IM3) in DCT?

It is signal BB mixing with LO 3rd harmonic then folds back to desired RF band due to Tx RF (mainly PA) 3rd order nonlinearity:

$$I = \cos(\omega_{bb} t)\,,\mathrm{Q} = \sin(\omega_{bb} t)$$

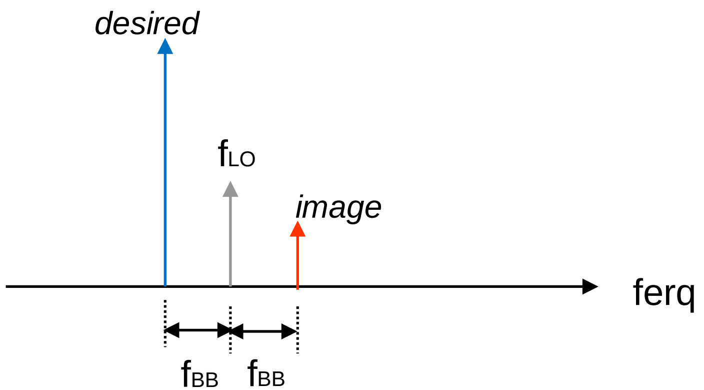
$$LO_I = \cos(\omega_{LO} t) + \alpha\cos(3\omega_{LO} t)\,, \qquad LO_Q = LO_I \xrightarrow{shift} \frac{T_{LO}}{4} = sin(\omega_{LO} t) + \alpha\cos(3\omega_{LO} t + \frac{3}{2}\pi)$$

$$RF_I = \mathrm{I} \times LO_I = 0.5\cos\big((\omega_{LO}+\omega_{bb})t\big) + 0.5\cos\big((\omega_{LO}-\omega_{bb})t\big) + \alpha'\cos\big((3\omega_{LO}+\omega_{bb})t\big) + \alpha'\cos\big((3\omega_{LO}-\omega_{bb})t\big)$$

$$RF_Q = \mathrm{Q} \times LO_Q = -0.5\cos\big((\omega_{LO}+\omega_{bb})t\big) + 0.5\cos\big((\omega_{LO}-\omega_{bb})t\big) + \alpha'\cos\big((3\omega_{LO}+\omega_{bb})t\big) - \alpha'\cos\big((3\omega_{LO}-\omega_{bb})t\big)$$

Assuming low-side transmission (image at $\cos\big((\omega_{LO}+\omega_{bb})t\big)$ goes away assuming prefect IRR)):

$$\boldsymbol{RF_{out} = RF_I + RF_Q = \cos\big((\omega_{LO}-\omega_{bb})t\big) + \alpha\cos\big((3\omega_{LO}+\omega_{bb})t\big)}$$



Assuming finite DC offset and IRR

Impairments of DCT: CIM3 'Cont

If RFout of the I/Q up-converter passes through a weakly none-linear block such as PA that has finite 3rd order distortion:

$$\gamma_3\,(RF_{out})^3 = \gamma_3\big(\cos((\omega_{LO}-\omega_{bb})t) + \alpha\cos((3\omega_{LO}+\omega_{bb})t)\big)^3$$

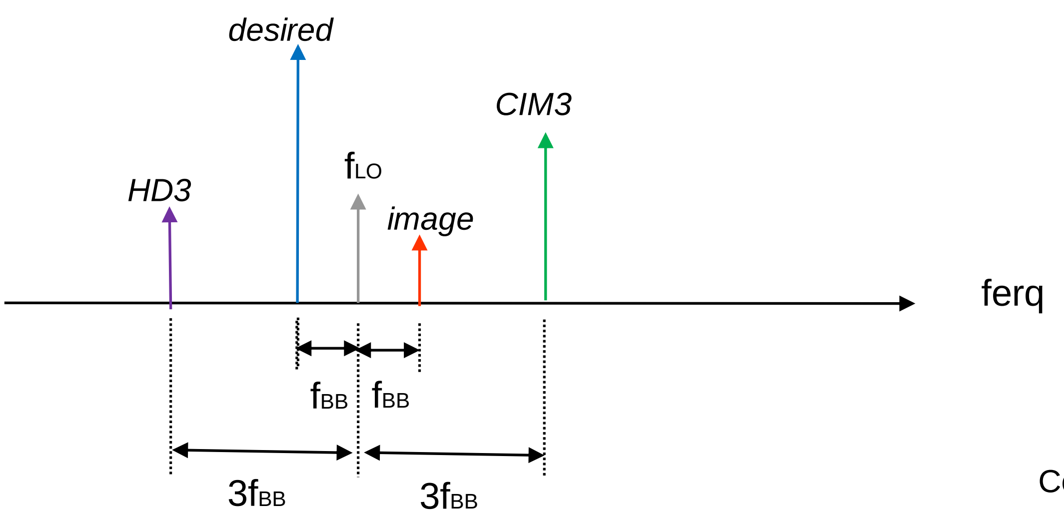
$$= \gamma_3\big((cos(\omega_{LO}-\omega_{bb})t)^2 + \alpha^2(cos(3\omega_{LO}+\omega_{bb})t)^2 + \alpha\cos((\omega_{LO}-\omega_{bb})t) \times \cos((3\omega_{LO}+\omega_{bb})t)\big) \times cos((\omega_{LO}-\omega_{bb})t) + ..$$

$$= \gamma_3\ (cos(\omega_{LO}-\omega_{bb})t + \alpha cos(\omega_{LO}+3\omega_{bb})t\ )$$

CIM3

The CIM3 falls on the opposite side of the desired signal. Its value is set by:

- LO 3rd harmonic component
- RF amplifier (PA) 3rd order distortion
- Rejection of the 3LO up-converted signal before reaching PA



Assuming finite DC offset and IRR

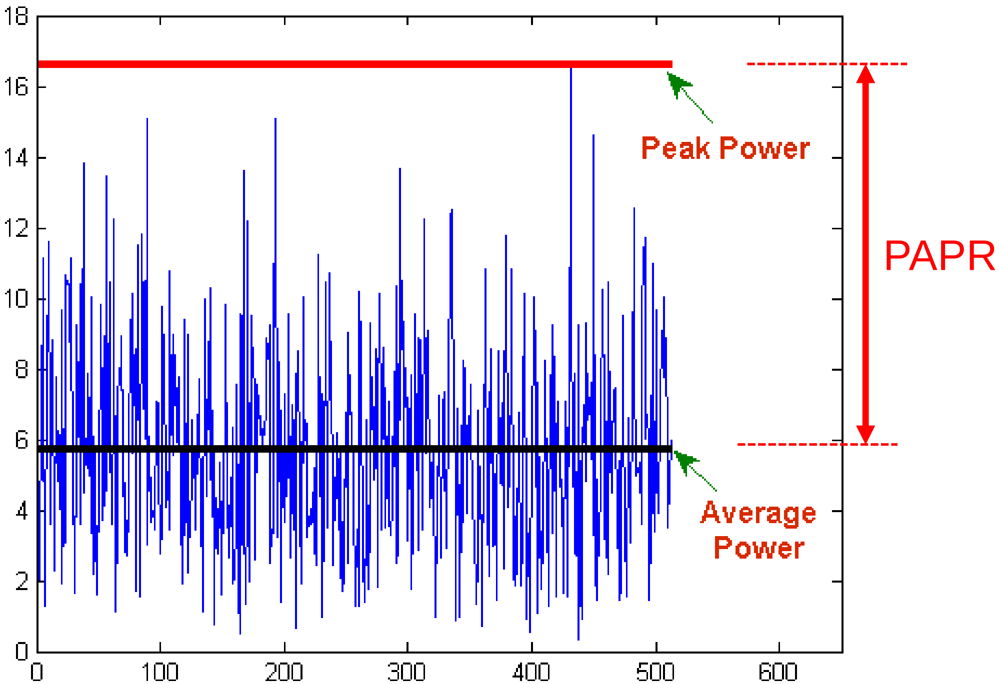
Impairments of DCT: CIM3 'Cont

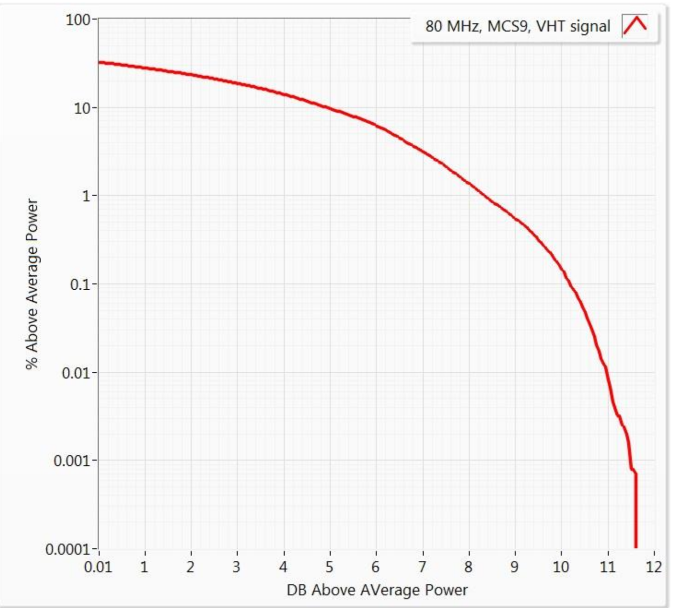
Methods to improve Tx CIM3:

1. Reduce LO 3rd harmonic:
   - Use the Weldon harmonic-rejection scheme
   - Use 33% duty cycle LO (no 3rd harmonic)
2. Insert an LC bandpass filter after the I/Q combiner (before PA) to filter out 3LO up-converted component
3. Linearize PA without jeopardizing its efficiency
4. Other (see references)

The issue of the Peak to Average Power Ratio (PAPR):

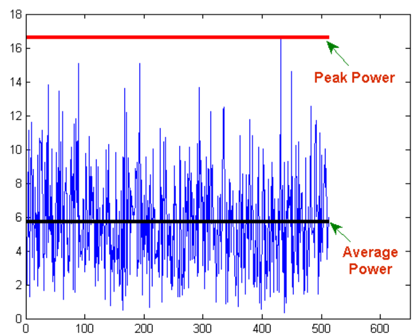
Different signal modulations result in different peak to average power ratio. For example, CW tone has 3dB PAPR. On the other hand, a 64QAM OFDM signal has ~10dB PAPR.



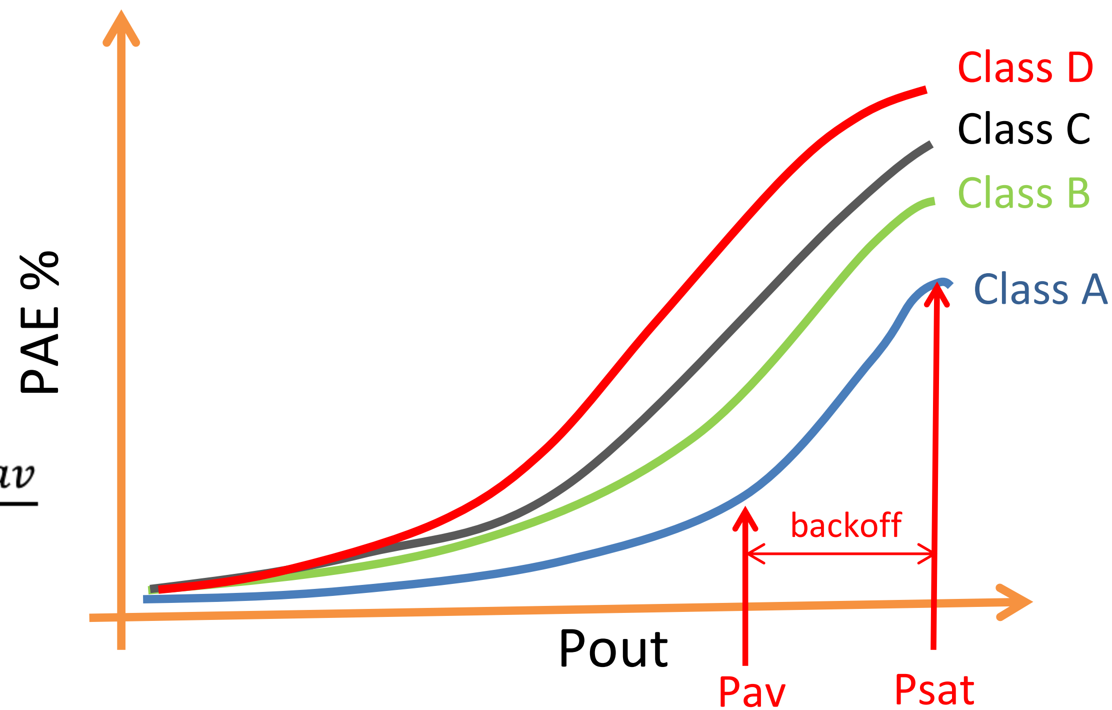


In fact, the “peak” has a Gaussian distribution with probability function. The 10dB peak for WiFi 11ac OFDM corresponds to ~0.1% probability. Clipping the OFDM signal at 10dB results in an EVM floor (distortion) of ~-47dB. Tx has to accommodate this PAPR to meet target EVM

Impact of PAPR on Tx/PA efficiency:

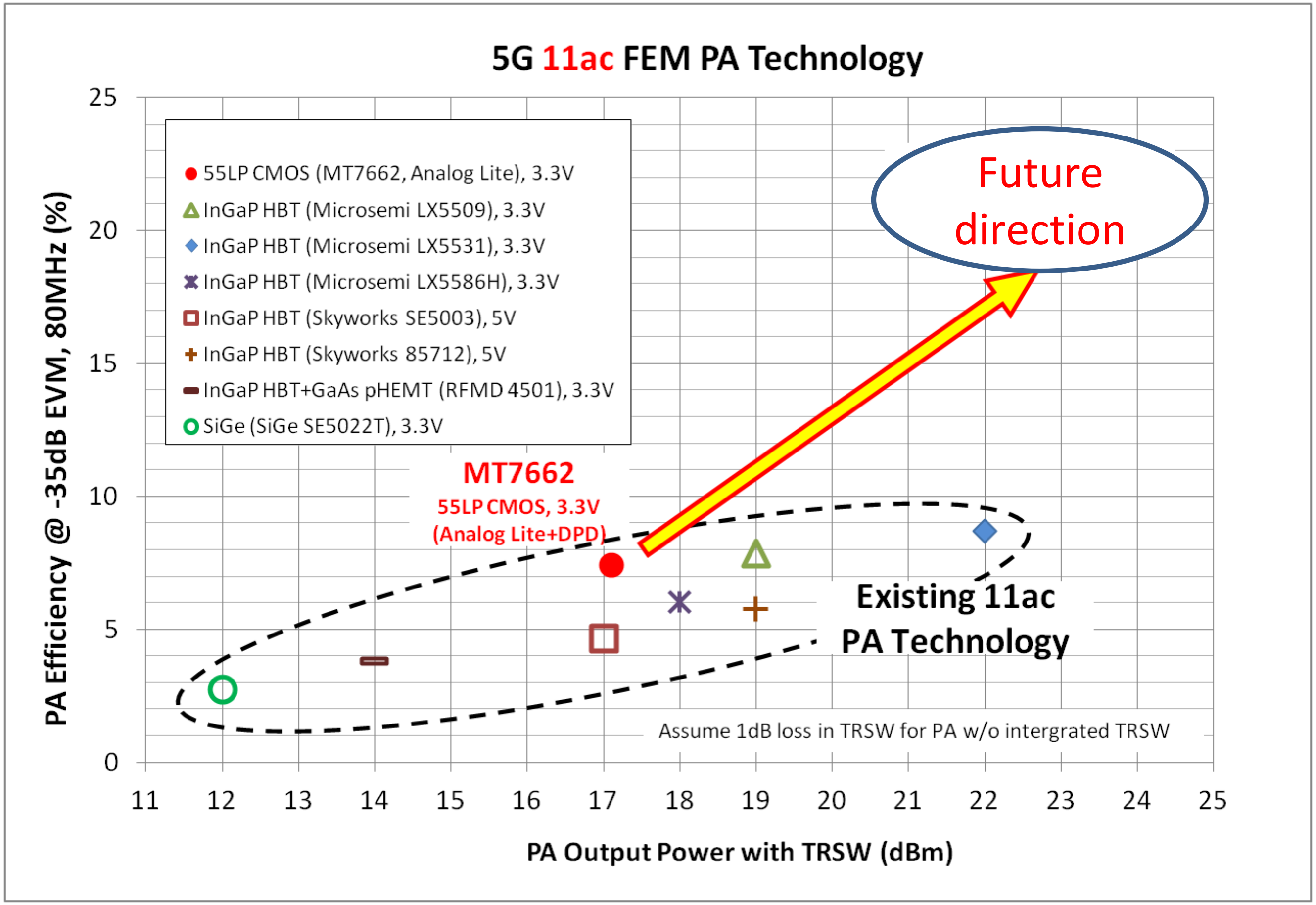


$$Efficiency\ \eta = \frac{P_{out\_av}}{P_{DC}}$$



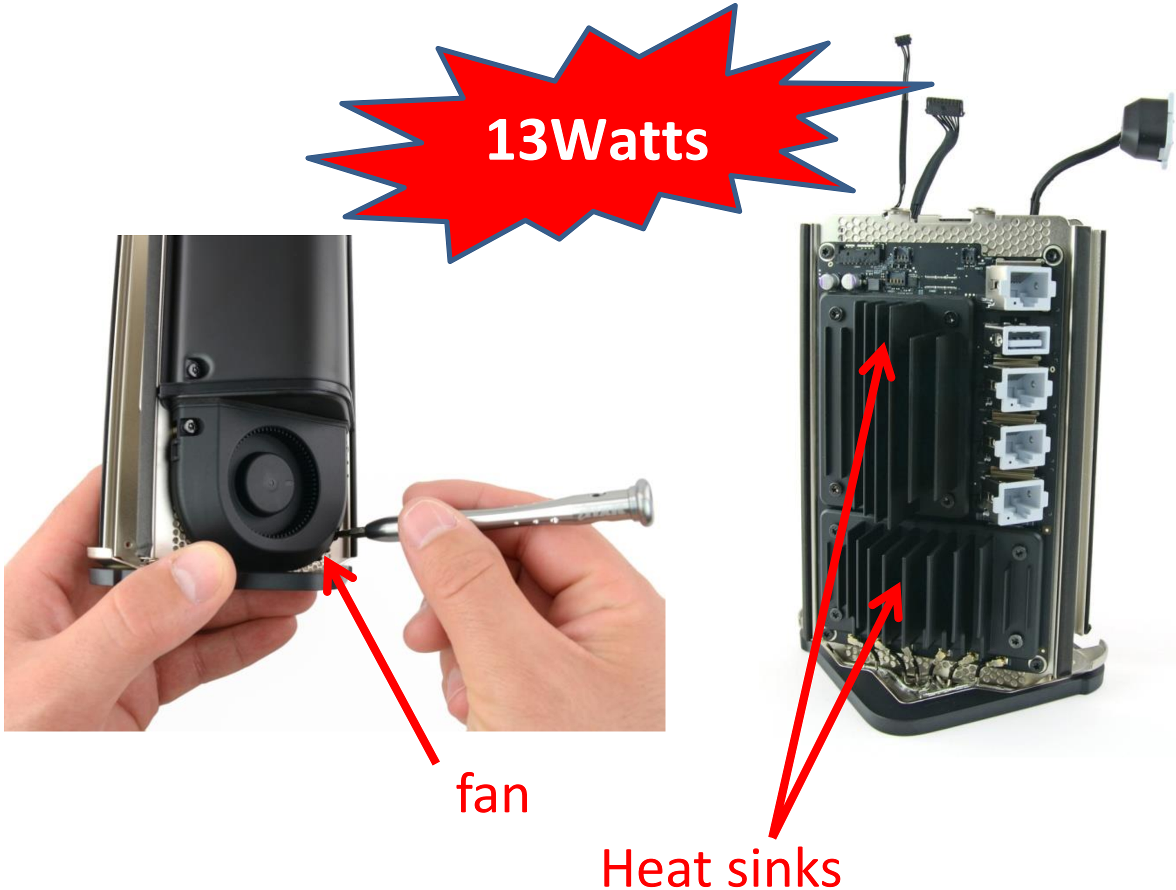
- Regardless of PA-type, severe PA efficiency loss occurs due to backoff. PAE is <10% for class AB PA and <15% for class D for 8dB backoff from Psat.
- For Pout of 24dBm, 10% efficiency means 2.5W P_{DC}

State of the art PA efficiency for WiFi 11ac 5GHz:



- Terrible efficiency even using GaAs and 5V supply!

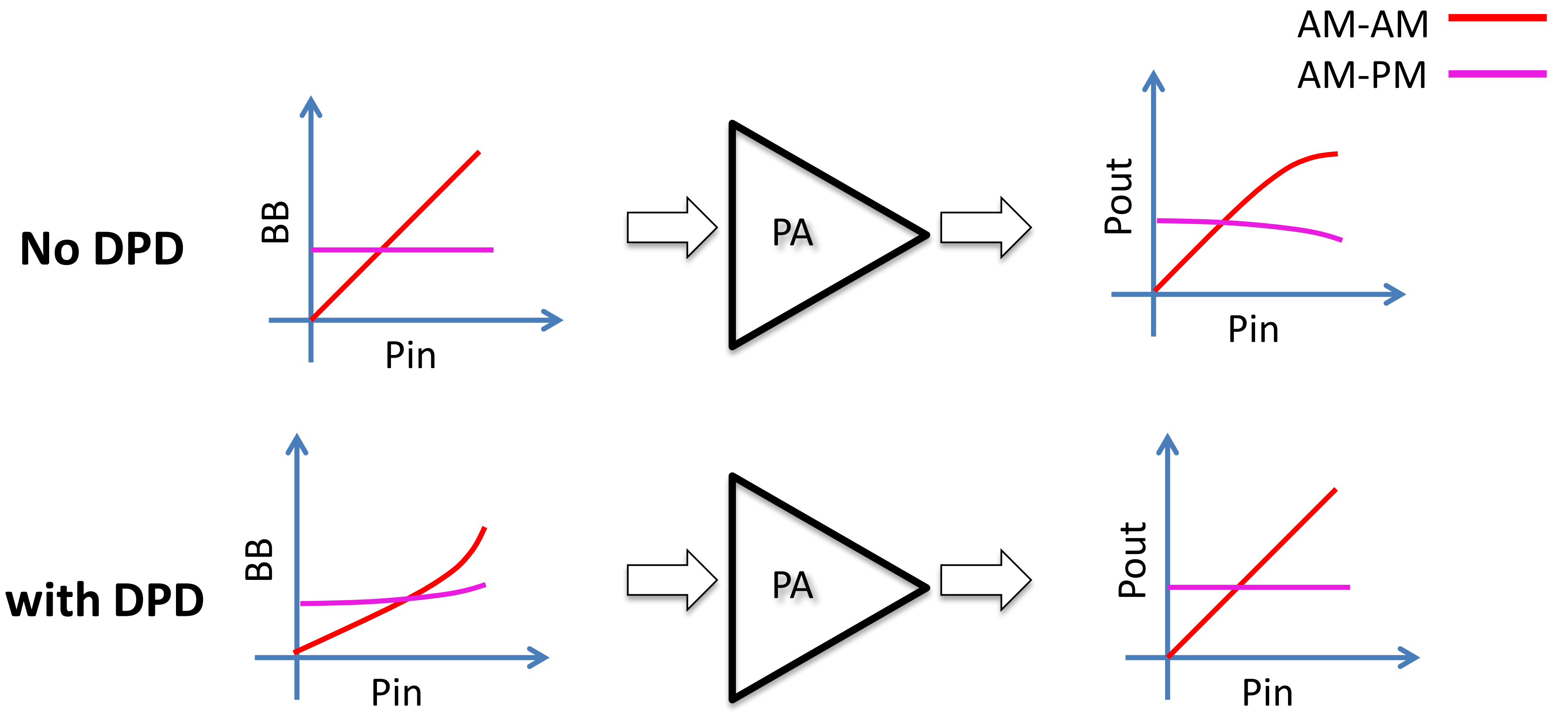
Why Tx efficiency is important??



- WiFi router from Apple
- Dual-band dual concurrent
- 4x4 a/b/g/n/ac

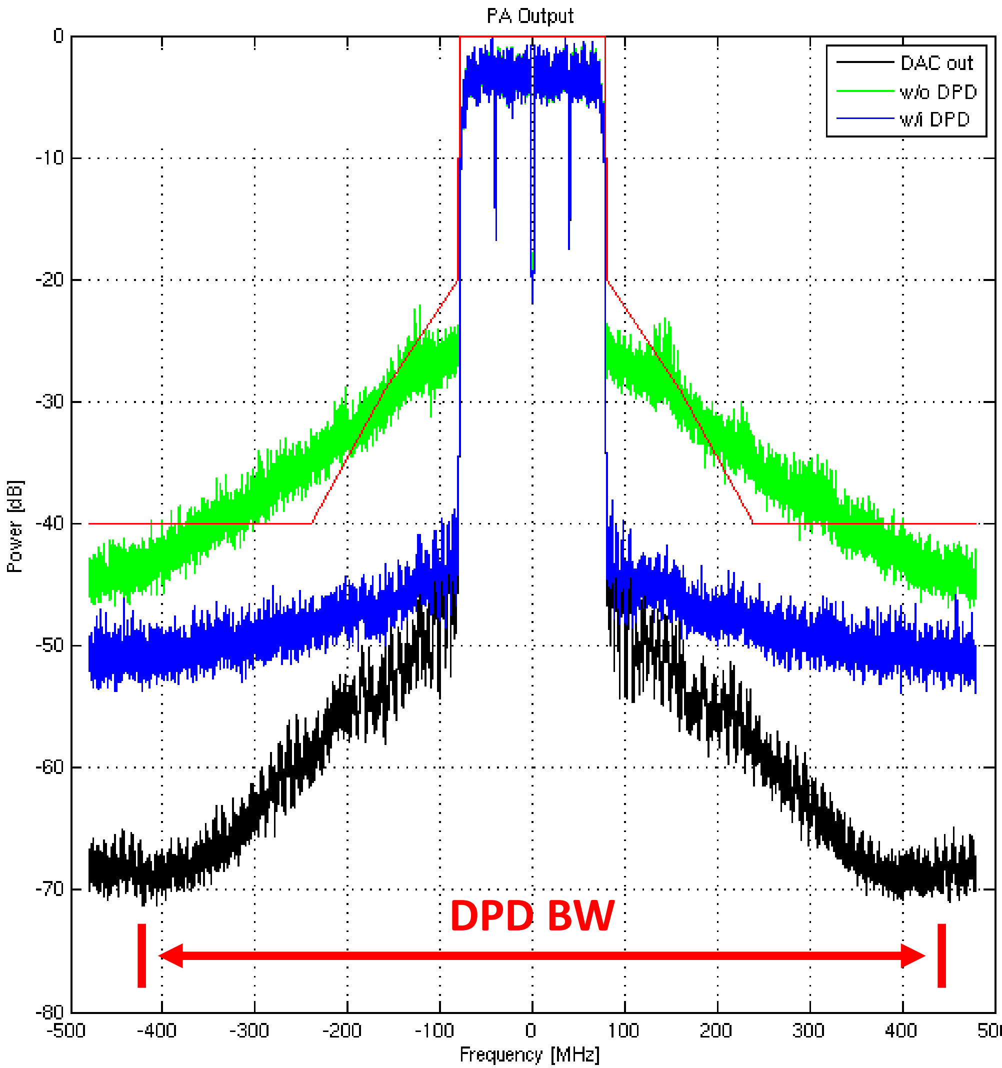
- Typical WiFi AP spends $1~$6 on heat sinks alone, not including fans
- Better efficiency can lower WiFI AP cost
- Cellular can also benefit → switch to solar-powered towers
- Longer talk time for hand-held devices

Digital pre-distortion (DPD) to improve Tx linearity



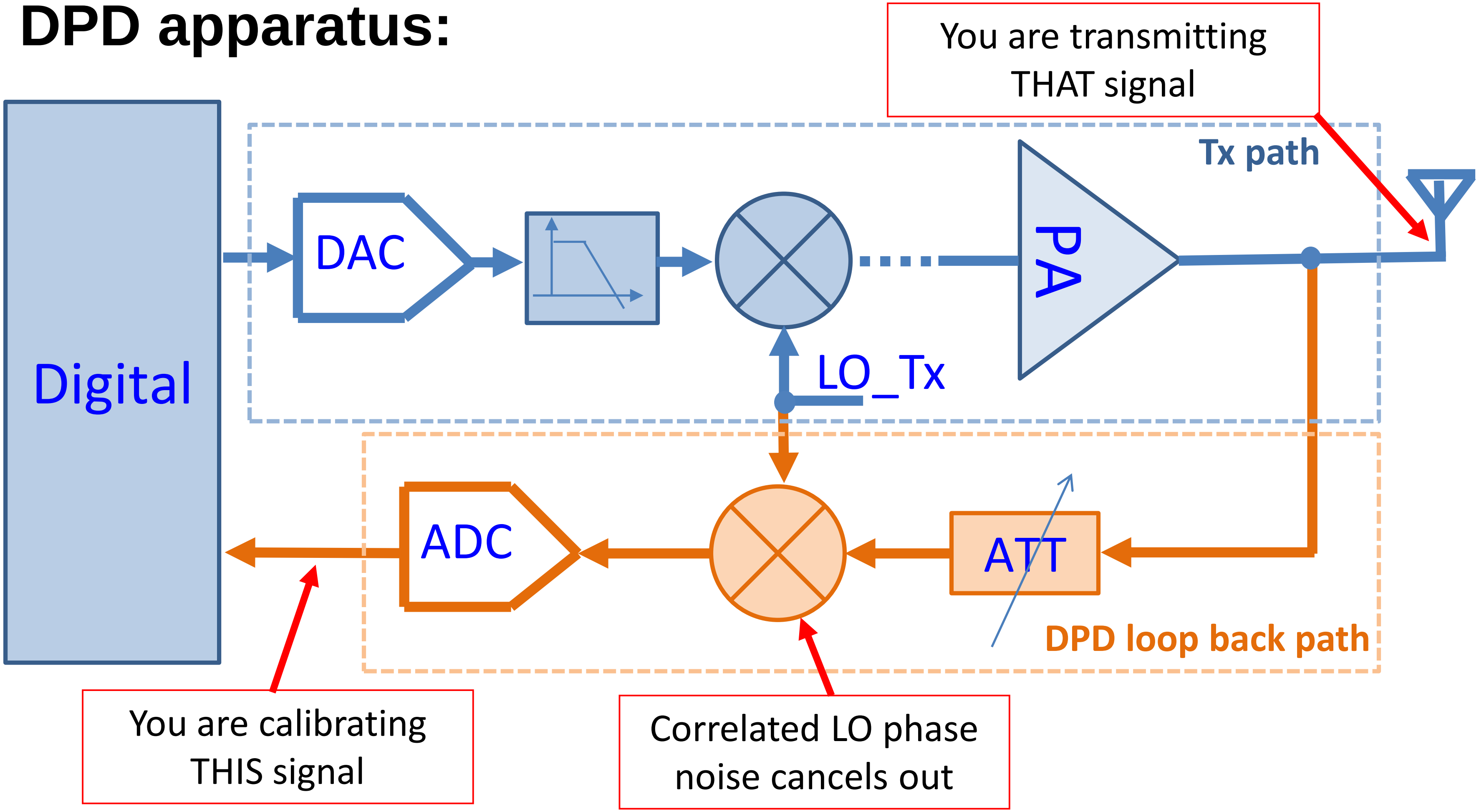
- Tx linearity is usually dominated by PA
- PA linearity can be modeled as AM-AM/PM distortion
- digital I/Q baseband signals are pre-distorted in amplitude and phase to compensate that of PA

DPD in frequency domain:



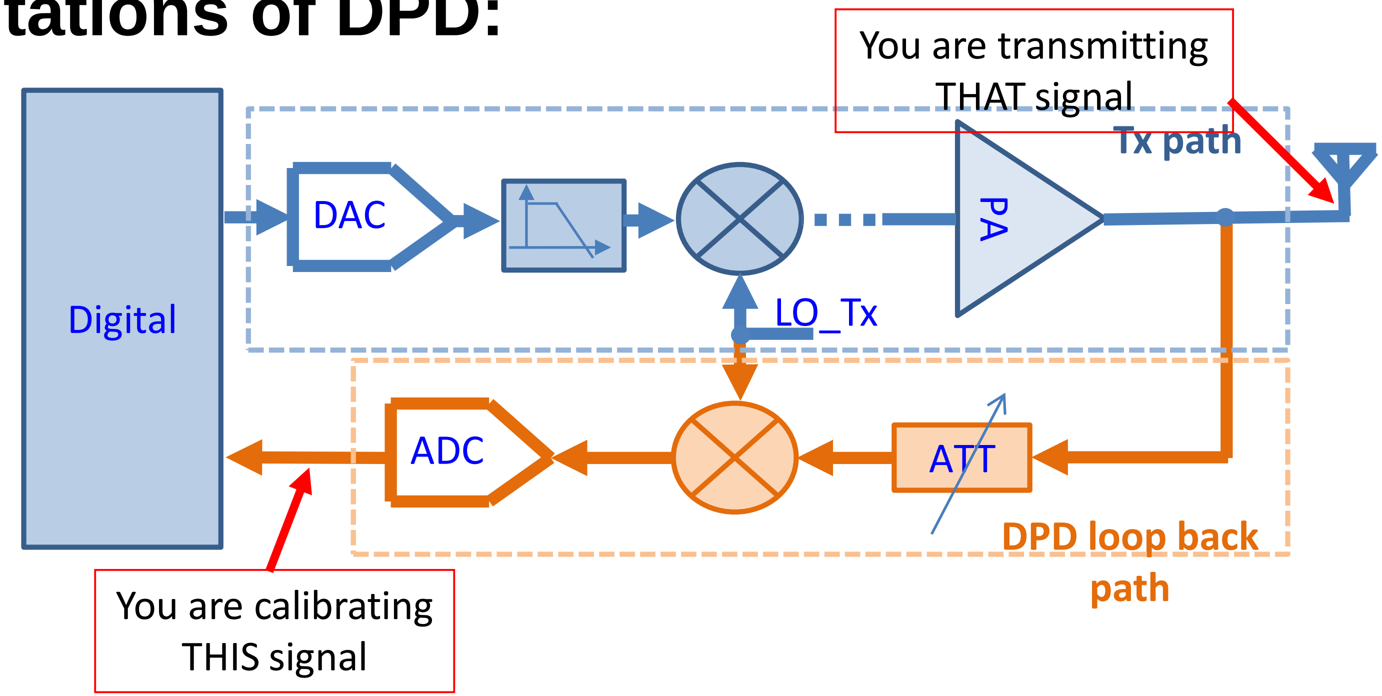
- DPD bandwidth can be as high as ~5x signal BW:
  →no analog filtering should exist in Tx path over DPD BW for DPD to do its job
  →Wider sensing BW is needed (for system with memory)

DPD apparatus:



- DPD apparatus down-converts PA characteristics to digital, which inverts it by pre-distorting input Tx signal

Limitations of DPD:



- integrity of DPD loopback path (needs EVM ~15dB better than Tx)
- PA training sequence and pattern
- digital FE resolution
- coupling between main Tx path and DPD path
- DPD interpolation error (for lookup table) or polynomial truncation error
- memory effects (will discuss later)

→ All these errors result in DPD floor (needs to be ~10dB better than target EVM)

References:

[1] YH Chen et al, “An LTE SAW-Less Transmitter Using 33% Duty-Cycle LO Signals for Harmonic Suppression,” *in conf Proc. ISSCC 2015*, pp 172-173

[2] B. Razavi, *RF Microelectronics* , Prentice Hall Ptr. 1998.

[3] Lu Ye, *et al*, “Design Considerations for a Direct Digitally Modulated WLAN Transmitter With Integrated Phase Path and Dynamic Impedance Modulation,” IEEE JSSC, Vol. 48, No. 12, Dec 2013.

[4] Yuen Hui Chee, Fatih Golcuk, Toru Matsuura, Christopher Beale, James F. Wang, and Osama Shanaa, “A Digitally Assisted CMOS WiFi 802.11ac/11ax Front-End Module Achieving 12% PA Efficiency at 20dBm Output Power with 160MHz 256QAM OFDM Signal,” *ISSCC Dig. Tech. papers*, pp 292-293, Feb 2017

[5] Qorvo RFFM8505 FEM Datasheet, https://www.rfmd.com/

[6] YH. Chung, et. al., “Dual-band Integrated Wi-Fi PAs with Load-Line Adjustment and Phase Compensated Power Detector”, RFIC Dig. of Tech. Papers, pp. 223-226, May 2015

[7] C.P. Huang, et al., “A Highly Integrated Single Chip 5-6 GHz Front-end IC Based on SiGe BiCMOS that enhances 802.11ac WLAN Radio Front-End Designs”, RFIC Dig. of Tech. Papers, pp. 227-230, May 2015