TSEK38: Radio Frequency Transceiver Design
Lecture 8: Transmitter Synthesis (I)

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Lecture schedule

w4:
- Le1: Introduction (Ch 1)
- Le2: Fundamentals of RF system modeling (Ch 2)
- Le3: Superheterodyne TRX design (Ch 3.1)

w6:
- Le4: Homodyne TRX design (Ch 3.2)
- Le5: Low-IF TRX design (Ch 3.3)
- Le6: Systematic synthesis (calculations) of RX (Ch 4)

w7:
- Le7: Systematic synthesis (continued)
- Le8: Systematic synthesis (calculations) of TX (Ch 5)

w8:
- Le9: Systematic synthesis (continued)

Lab schedule

w6:
- We: Lab1a (after Le6): 15-19 (ASGA)
- Th: Lab1b: 17-21 (SOUT)

w7:
- We: Lab1c (after Le8): 15-19 (SOUT)
- Th: Lab1d: 17-21 (EGYP)

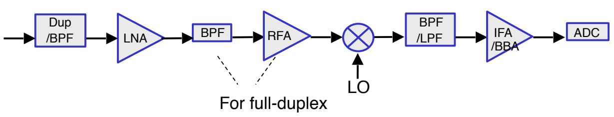
Instructions:
- One long lab (4 x 4 h).
- Lab manual in the Lisam *Course Documents/2019/Lab* folder.
- Supervision (Ted) available at the times above.
- To pass: complete and document the exercises in the lab manual, go through with Ted.

Summary of lecture 6-7: RX synthesis

- Key design parameters, RX:
  - sensitivity: overall noise figure (4.2)
  - intermodulation: 3rd order distortion, IP3 (4.3) also IP2
  - single-tone desensitization (4.4, not!)
  - adjacent/alternate channel selectivity: channel filter, phase noise, (4.5)
  - interference blocking: channel filter, phase noise, (4.5)
  - dynamic range: AGC, ADC (4.6).
- System design (4.7)

4.7.3 Performance evaluation

Line-up analysis



- Some specs already known:
  - Duplexer/switch loss (NF)
  - RF BPF loss (NF)
  - IP2 of downconversion mixer
  - Mixer gain, if passive
  - BW of filters

Distribution of G, NF, IIP3, (IIP2) ?

Performance evaluation

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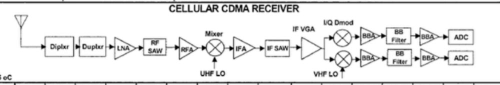
Table 4.3 Electrical performance evaluation example of a Cellular band CDMA receiver

CELLULAR CDMA RECEIVER



25 oC

25 oC		Diplxr	Duplxr		RF SAW		MIXER				I/QMIX	BB_AMP	BB/FILTR	BB_AMP		Total
Current (mA)								10								45
P_Gain dB		-0.4	-2.5	14	-2.5	10	-6	10	-11	18.49	30			35		95.09
V_Gain dB		-0.4	-2.5	14	-2.5	10	-6	10	-1	18.49	30			35		105.09
Fltr Rej (	inTx Band	52		In Tx Band	25			@ 900 kHz	38			@ 900 kHz	45			
(dB)	n Rx band	45						@ 1.7 MHz	50			@ 1.7 MHz	55			
out dBm	-108	-108.4	-110.9	-96.9	-99.4	-89.4	-95.4	-85.4	-96.4	-77.9073	-47.9073	-47.9073	-47.9073	-12.9073	-12.9073	
out mV	0.00089	0.00085	0.00064	0.0032	0.0024	0.00758	0.0038	0.01201	0.010702	0.08997	2.84525	2.84525	2.84525	160	160	
NF dB		0.4	2.5		2.5				11	10	25		45	38	59	
Cascad NF	5.79	5.79	5.39	2.89	12.62	10.12	18.96	12.96	22.76	11.76	25.50	45.82	45.82	38.17		
NF Contr	100.00%	28.88%	22.47%	13.30%	1.59%	5.50%	1.08%	0.00%	1.68%	16.40%	8.13%	0.00%	0.82%	0.16%	0.01%	
IIP3 dBm	100.00	100.00	100.00	8.00	100.00	10.00	17.00	12.00	32.00	-20.00	-25.00	100.00	15.00	-21.00	40	
Cascad IIP3	-6.26	-6.26	-6.66	-9.16	4.92	2.42	13.26	9.64	23.43	-43.92	-25.41	15.00	15.00	-21.01		
IIP3 Cont	100.00%	0.00%	0.00%	1.92%	0.00%	17.14%	34.20%	27.17%	2.72%	0.07%	15.25%	0.00%	1.53%	0.00%	0.00%	

Rx an Tx Key Parameters — **Synthesizer LO Phase Noise & Spurs**

Rx :	FER =	5.00E-03		Sd(dBm) =	-101	BW(Hz) =	1.23E+06		Sp,adj =	-85	Sp,atl =	-85
	CNR(dB)=	-2							Nphase=	-137	Nphase=	-140
Tx :	PTx(dBm)	23	23	TxPhsNois								
				in Rx band	-138	dBm/Hz						

Receiver Performance:

			Margin (dBc)	Spec	
1. Sensitivity					
MDS = -174 + 10 log(BW) + CNR + NF =	**-109.16**	dBm	**5.16**	-104	dBm
2. Intermodulation Spurious Response Attenuation					
IMD = [2(IIP3 - Sd) - CNR] /3 =	**-37.54**	dBm	**5.46**	-43	dBm
3. Single Tone Desensitization					
IST = Sd-CNR+2*IIP3-2(PTx-Rj_dplx) -40log(M_indx) =	**-24.79**	dBm	**5.21**	-30	dBm

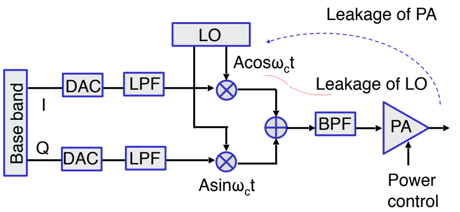
Systematic Transmitter Synthesis (I)

- 5.1 Introduction
- 5.2 Transmission power and spectrum
- 5.3 Modulation accuracy
- 5.4 Adjacent and Alternate Channel Power
- (5.5 Noise emissions)

5.1 Introduction

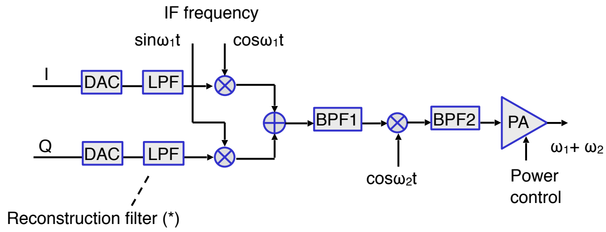
- FDD/TDD.
- Direct-conversion, heterodyne.
- Less filter requirements.
- ”Deterministic”, stronger signal.
- Parameters: (maximum) output power, linearity, EVM, ACPR, emissions (spectrum mask), power consumption. (Noise not that important.)
- Nonlinearities mostly from the PA (last amplifier).
- Power consumption/efficiency set mostly by the PA.
- AGC/gain stepping.

One-step (direct conversion) transmitter



- Up-conversion is performed in one step, $f_{LO} = f_c$.
- Simple modulation, e.g. QPSK can be done in the same process.
- BPF suppresses harmonics.
- LO must be shielded to reduce corruption.
- I and Q paths must be symmetrical and LO in quadrature, otherwise crosstalk.

Two-step transmitter



Advantage:

- Better IQ matching since ω_1 is lower
- Carrier far from LO's frequency

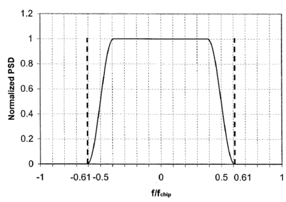
(*) Wikipedia: "a reconstruction filter is used to construct a smooth analog signal from a digital input, as in the case of a digital to analog converter (DAC) or other sampled data output device.

5.2 Transmission power and spectrum

- Output power defined differently in different standards:
  - GSM, WCDMA, (LTE): at antenna port (**ARP**).
  - other older systems (e.g. CDMA): effective radiated power (**ERP**) = (power supplied to antenna) * (antenna gain relative to a half-wave dipole in a given direction), gain = 2.15 dBi
    ERP[dB] = $TX_{pwr\_ant} + G_{ant} - 2.15$,
  - or effective isotropic radiated power (**EIRP**) = (power supplied to antenna) * (antenna gain relative to a isotropic antenna), gain = 0 dBi
    EIRP[dB] = $TX_{pwr\_ant} + G_{ant}$.
  - Usually **ARP** is used.

Transmission power and spectrum

- Transmission power measured in frequency domain = integrated power over bandwidth.
- E.g. WCDMA, BW=3.84 MHz, $(1+\alpha)$ RRC, $\alpha = 0.22$ => 1.22 x 3.84 = 4.68 MHz BW for integration.
- Some standards (e.g. CDMA IS-95): not well defined.



Power measurements

- Power probe + instrument (or probe/USB + computer)

Allowed transmitted output power

p. 137

Table 3.2. Maximum output power of different system mobile stations

Systems	Power Class	Nominal Power (dBm)	Tolerance (dB)	Note
AMPS	III	28	-4, +2	ERP
CDMA Cell	III	23	+7	ERP
CDMA PCS	II	23	+7	EIRP
GSM 900	IV	33	-2, +2	Ant. Port
GSM 1800	I	30	-2, +2	Ant. Port
TDMA	III	28	-4, +2	ERP
WCDMA	IV	21	-2, +2	Ant. Port
WLAN (802.11ac)		23	PAPR=8 => peak >30 dBm	

- Terminal (mobile phone), uplink, UE (user equipment)
- Average output power. E.g. WCDMA PAPR 4-6 => peak may be up to 29 dBm

Allowed transmitted output power

- LTE:

Release 10 22 3GPP TS 36.104 V10.12.0 (2016-12

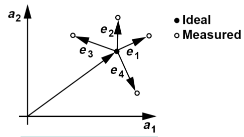
Table 6.2-1: Base Station rated output power

BS class	PRAT
Wide Area BS	- (note)
Local Area BS	≤ + 24 dBm (for one transmit antenna port) ≤ + 21 dBm (for two transmit antenna ports) ≤ + 18 dBm (for four transmit antenna ports) < + 15 dBm (for eight transmit antenna ports)
Home BS	≤ + 20 dBm (for one transmit antenna port) ≤ + 17 dBm (for two transmit antenna ports) ≤ + 14dBm (for four transmit antenna ports) < + 11dBm (for eight transmit antenna ports)
NOTE: There is no upper limit for the rated output power of the Wide Area Base Station.	

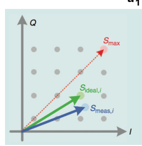
- Above is for downlink BS (base station).

5.3 Modulation accuracy (linearity)

- 5.3.1 Error Vector Magnitude (EVM): the deviation of the constellation points from their ideal positions.



$S_{ideal} - S_{meas} = e$



EVM_{RMS}:

$$EVM = \left[\frac{E\left\{\left|\bar{a}'(k_1) - \bar{a}(k_1)\right|^2\right\}}{E\left\{\left|\bar{a}(k_1)\right|^2\right\}}\right]^{\frac{1}{2}} = \left[\frac{E\left\{\left|\bar{e}(k_1)\right|^2\right\}}{E\left\{\left|\bar{a}(k_1)\right|^2\right\}}\right]^{\frac{1}{2}}. \quad (5.3.11)$$

- EVM is the main TRX linearity measure (limitation) in WLAN.

EVM

- EVM measured in % or dB.
- Typically 5-15 %, -30 — -20 dB

Table 6.5.2-1 EVM requirements

Modulation scheme for PDSCH	Required EVM [%]
QPSK	17.5 %
16QAM	12.5 %
64QAM	8 %

LTE rel. 10

EVM [%]	EVM [dB]
1	–40,0
1,5	–36,5
2	–34,0
2,5	–32,0
3	–30,5
3,5	–29,1
4	–28,0
5	–26,0
6	–24,4
7	–23,1
8	–21,9
9	–20,9
10	–20,0

EVM [dB] = (E [%] /100)² in dB

Modulation	Coding Rate	802.11n RCE (dB)	802.11ac RCE (dB)
BPSK	1/2	-5	-5
QPSK	1/2	-10	-10
QPSK	3/4	-13	-13
16QAM	1/2	-16	-16
16QAM	3/4	-19	-19
64QAM	2/3	-22	-22
64QAM	3/4	-25	-25
64QAM	5/6	-28	-27
256QAM	3/4	N/A	-30
256QAM	5/6	N/A	-32

WLAN 802.11ac

For CDMA waveform, a quality factor is defined:

$$\rho \cong \frac{1}{1 + EVM^2} \quad (5.3.13a)$$

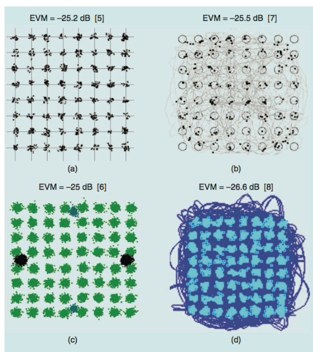
EVM^2 can be considered as 1/SNR

EVMs

$$EVM_{max} = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N} |S_{ideal,i} - S_{meas,i}|^2}}{|S_{max}|}$$

$$EVM_{RMS} = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N} |S_{ideal,i} - S_{meas,i}|^2}}{\sqrt{\frac{1}{M}\sum_{i=1}^{M} |S_{ideal,i}|^2}}$$

EVM_{RMS} EVM_{MAX}



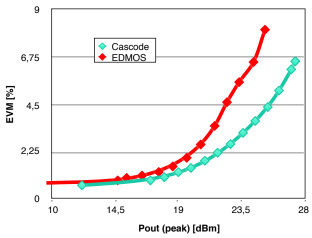
- Same EVM (64 QAM) but different definitions:
(a) + (c) = EVM_{RMS},
(b) + (d) = EVM_{max}.

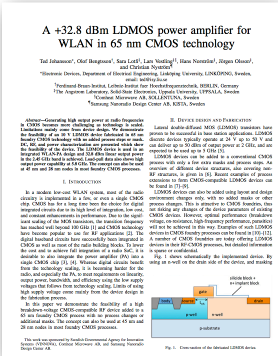
"Additional readings" folder

Ref: Vigilante et al., IEEE Solid-State Magazine, No. 3, 2017, p. 36.

EVM (example)

- WLAN CMOS PA (65 nm)





A +32.8 dBm LDMOS power amplifier for WLAN in 65 nm CMOS technology

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Abstract—Generating high output power at radio frequencies in CMOS becomes more challenging as technology is scaled. Limitations mainly come from device design. We demonstrate the feasibility of an 10 V LDMOS device fabricated in 65 nm foundry CMOS technology with no added process steps or mask. DC, RF, and power characterization are presented which show the feasibility of the device. The LDMOS device is used in an integrated WLAN-PA design and 32.8 dBm linear output power in the 2.45 GHz band is achieved. Load-pull data also shows high output power capability at 5.8 GHz. The concept can also be used at 45 nm and 28 nm nodes in most foundry CMOS processes.

I. Introduction

In a modern low-cost WLAN system, most of the radio circuitry is implemented in a few, or even a single CMOS chip. CMOS has for a long time been the choice for digital integrated circuits due to its high level of integration, low cost, and constant enhancements in performance. Due to the significant scaling of the MOS transistors, the transition frequency has reached well beyond 100 GHz [1] and CMOS technology have become popular to use for RF applications [2]. The digital baseband circuits have successfully been integrated in CMOS as well as most of the radio building blocks. To lower the cost and to achieve full integration of a radio SoC, it is desirable to also integrate the power amplifier (PA) into a single CMOS chip [3], [4]. Whereas digital circuits benefit from the technology scaling, it is becoming harder for the radio, and especially the PA, to meet requirements on linearity, output power, bandwidth, and efficiency using the low supply voltages that follows from technology scaling. Limits of using high supply voltage come mainly from the device design in the fabrication process.

In this paper we demonstrate the feasibility of a high breakdown-voltage CMOS-compatible RF device added to a 65 nm foundry CMOS process with no process changes or additional masks. The concept can also be used at 45 nm and 28 nm nodes in most foundry CMOS processes.

This work was sponsored by Swedish Governmental Agency for Innovation Systems (VINNOVA), Comheat Microwave AB, and Samsung Nanoradio Design Center AB.

II. Device design and Fabrication

Lateral double-diffused MOS (LDMOS) transistors have proven to be successful in base station applications. LDMOS discrete devices typically operate at 24 V up to 50 V and can deliver up to 50 dBm of output power at 2 GHz, and are expected to be used up to 5 GHz [5].

LDMOS devices can be added to a conventional CMOS process with only a few extra masks and process steps. An overview of different device structures, also covering non-RF structures, is given in [6]. Recent examples of process extensions to form CMOS-compatible LDMOS devices can be found in [7]–[9].

LDMOS devices can also be added using layout and design environment changes only, with no added masks or other process changes. This is attractive to CMOS foundries, thus not risking any changes of the device parameters of existing CMOS devices. However, optimal performance (breakdown voltage, on-resistance, high-frequency performance, parasitics) will not be achieved in this way. Examples of such LDMOS devices in CMOS foundry processes can be found in [10]–[12]. A number of CMOS foundries are today offering LDMOS devices in their RF-CMOS processes, but detailed information is sparse or confidential.

Fig. 1 shows schematically the implemented device. By using an n-well on the drain side of the device, and masking

silicide block + n+ implant block
gate
body
source
L_{ch}
drain
p-well
n-well
p-substrate

Fig. 1. Cross-section of the fabricated LDMOS device.

Johansson et al., EuMIC 2013

EVM degradation

5.3.2 Intersymbol interference (ISI)

5.3.3 Close-in phase noise of LO

5.3.4 Carrier leakage

5.3.5 Other factors

- 5.3.5.1 IQ imbalance
- 5.3.5.2 Nonlinearities
- 5.3.5.3 In-channel bandwidth noise
- 5.3.5.4 Reverse LO modulation (not)

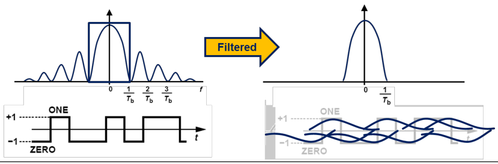
Total EVM:

$$EVM_{Tx}^2 = EVM_{ISI}^2 + EVM_{PN}^2 + EVM_{CL}^2 + EVM_{IR}^2 + EVM_{nonlin}^2 + +EVM_{noise}^2 + +EVM_{other}^2$$

EVM degradation

5.3.2 Intersymbol interference (ISI)

- Non-ideal filter => distortion in delay and magnitude
- Each pulse extends in time and spills to the time slot of other pulses. This is called Inter Symbol Interference (ISI).
- EVM degradation from filter/ISI in TX not a major problem since no tight filtering are used in modern designs.
- Typically **contribution < 5 %** and also can be compensated by predistortion.



EVM degradation

5.3.3 Close-in phase noise of LO

- Phase noise from VHF and UHF LO in the modulator and up-converter in the TX.
- If the synthesizer loop bandwidth is reasonably wide:

Noise power:

$$P_{Nphase} \cong 2 \cdot 10^{\frac{N_{phase}}{10}} \cdot BW_{synth\_loop}, \quad (5.3.25)$$

$$EVM_{Nphase} = \sqrt{P_{Nphase}} \cong \sqrt{2 \cdot 10^{\frac{N_{phase}}{10}} BW_{synth\_loop}}\,. \quad (5.3.26)$$

EVM degradation

1

- With several synthesizers:

$$EVM_{Nphase} = \sqrt{\sum_{k=1}^{n} P_{Nphase,k}}\,. \quad (5.3.27)$$

- Example (pp. 323-324):
  - Two LOs, 1.23 MHz BW for CDMA
    1. VHF, PN = -26 dBc over the BW
    2. UHF, PN = -28 dBc over the BW

$$EVM_{Nphase} = \sqrt{P_{Nphase\_VHF} + P_{Nphase\_UHF}} \cong \sqrt{10^{\frac{26}{10}} + 10^{\frac{28}{10}}} = 6.4\%\,.$$

  - Adding the EVM from a low-pass filter of 5 %, the combined EVM:

$$EVM_T = \sqrt{EVM_{ICI}^2 + EVM_{n,phase}^2} = \sqrt{0.05^2 + 0.064^2} = 8.1\%\,.$$

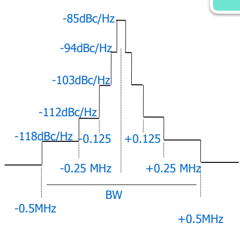
~ISI PN

EVM degradation: another view

2

$$EVM_{PN}^2 = 2 \times \sum_k 10^{\frac{PN(f_k)}{10}} \Delta f_k$$

- Example:
  We integrate over BW



$$EVM_{PN}^2 = 2 \times (250 \times 10^3 \times 10^{\frac{-118}{10}} + 125 \times 10^3 \times 10^{\frac{-112}{10}} + 62.5 \times 10^3 \times 10^{\frac{-103}{10}} + 31.25 \times 10^3 \times 10^{\frac{-94}{10}} + 15.62 \times 10^3 \times 10^{\frac{-85}{10}})$$

$$= 2.34 \times 10^{-4}$$

$$EVM_{PN} = 1.53 \times 10^{-2} = 1.53\%$$

EVM degradation

5.3.4 Carrier leakage

- DC offsets in the BB I and Q channels can cause carrier leakage (CL or CF or CFT):

$$a_I'(t) = I(t)\cos\phi(t) + \Delta I_{dc}$$

$$a_Q'(t) = Q(t)\sin\phi(t) + \Delta Q_{dc}\,,$$

output from modulator:

$$f_{Tx}(t) = a_I'(t)\cos\omega_c t - a_Q'(t)\sin\omega_c t$$
$$\cong A(t)\cos[\omega_c t + \varphi(t)] + \Delta_{dc}\cos(\omega_c t + \Delta\theta),$$

$$\Delta_{dc} = \sqrt{\Delta I_{dc}^2 + \Delta Q_{dc}^2}$$

$$\Delta\theta = \tan^{-1}(\Delta Q_{dc}/\Delta I_{dc}).$$

power ratio:

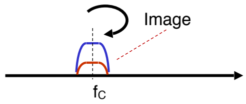
$$C_S = 10\log\frac{P_{CFT}}{P_{Tx}} = 20\log\frac{V_{CFT\_rms}}{V_{Tx\_avg}}$$

$$EVM_{CFT} = \sqrt{10^{\frac{C_S}{10}}} = \sqrt{\sum_{k=1}^{n} 10^{\frac{C_{S,k}}{10}}}$$

examples in the books p. 326

EVM degradation

5.3.5.1 IQ imbalance



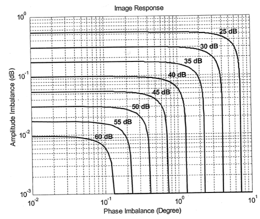
- IQ imbalance generate an image of the transmitted signal
- Similar to RX

$$IR = 10\log\frac{P_{Image}}{P_{Signal}}$$

$$IR = 10\log\frac{1+2(1+\delta)\cos\varepsilon+(1+\delta)^2}{1-2(1+\delta)\cos\varepsilon+(1+\delta)^2}$$

δ - gain imbalance
ε - phase imbalance

$$EVM_{IR}^2 = 10^{\frac{IR}{10}}$$



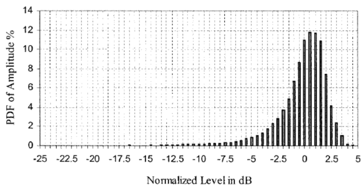
- In practice IR > -30dB → EVM_{IR} < 3.2%

see book p. 328 for details

EVM degradation

5.3.5.2 Nonlinearities

- For systems with varying modulation amplitude.
- Mostly from PA non-linearity.
- Amplitude probability distribution (PDF) of a modulated signal => PAPR

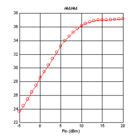


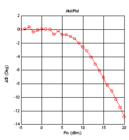
EVM degradation

- In the book, simple model of contribution from P_{-1dB} compression: $\Delta_{dB} = P_{Tx} - (P_{-1dB})_{out}$ which leads to modulation error of $e = 10^{\frac{\Delta_{dB}+1}{20}} - 1$

$$EVM_{nonlin} = \sum_k p(\Delta_{dB}(k)) \times (10^{\frac{\Delta_{dB}(k)+1}{20}} - 1)$$

- Typically 1-4 %.

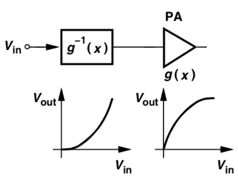


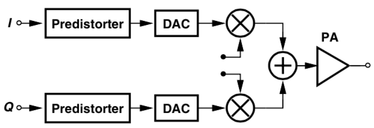


- In reality, most of the total EVM degradation may come from the PA if having high AM-AM and AM-PM distortion. Can be improved with digital predistortion (DPD).

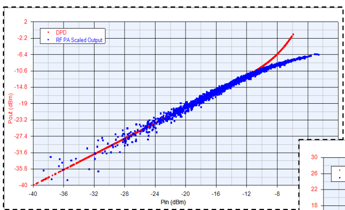
Digital predistortion (DPD)

- There are many linearization techniques, the most popular (especially in basestations) is digital predistortion.

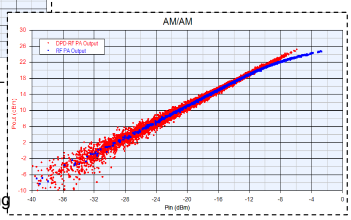




Predistortion (DPD)



Blue = undistorted
Red = added distortion



Blue = undistorted
Red = resulting after adding

EVM degradation

- 5.3.5.3 In-channel emission noise

  (Leakage of carrier with no information)

$$EVM_{noise} = \sqrt{10^{\frac{N_{in-ch-band} - Tx}{10}}}, \qquad (5.3.44)$$

- May be significant at low transmit power levels

5.3.6 Total EVM

- If EVM contributions are uncorrelated:

$$EVM_{total} = \sqrt{\sum_k EVM_k^2} = \sqrt{EVM_{ISI}^2 + \sum_{i=1}^{2} EVM_{Nphase,i}^2 + EVM_{CFT}^2 + EVM_{img}^2 + \cdots}\ . \qquad (5.3.46)$$

(please note the inconsistent names/indices of the different EVM contributions in the book)

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