TSEK38: Radio Frequency Transceiver Design
Lecture 9: Transmitter Synthesis (II)

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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)

Repetion of Lecture 8

- Systematic Transmitter Synthesis
  - Introduction
  - Transmission power and spectrum
  - Modulation accuracy

5.1 Introduction

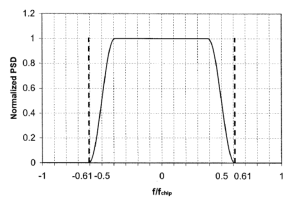
- FDD/TDD.
- Direct-conversion, heterodyne.
- Less filter requirements.
- ”Deterministic”, stronger signal.
- Parameters: (maximum) output power, linearity, EVM, ACPR, emissions (spectrum mask), power consumption. (Noise not that important.)
- Nonlinearities mostly from the PA (last amplifier).
- Power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

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.

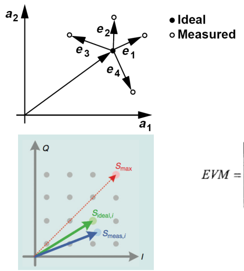
Transmission power and spectrum

- 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.



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}:

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

- 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:

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

EVM^2 can be considered as 1/SNR

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)

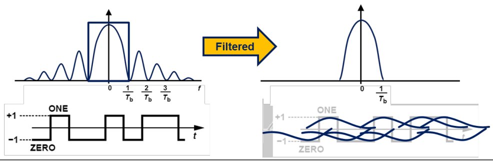
Total EVM:

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

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

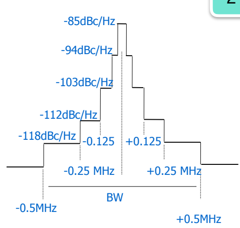
$$\boxed{EVM_{Nphase} = \sqrt{P_{Nphase}}} \cong \sqrt{2 \cdot 10^{\frac{N_{phase}}{10}} \, BW_{synth\_loop}}. \qquad (5.3.26)$$

EVM degradation: another view

2

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

- 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:

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

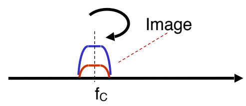
$$\boxed{EVM_{CFT} = \sqrt{10^{\frac{C_S}{10}}} = \sqrt{\sum_{k=1}^{n} 10^{\frac{C_{S,k}}{10}}}}$$

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

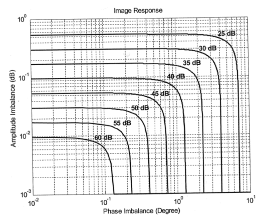


$$IR = 10\log\frac{P_{Image}}{P_{Signal}}$$

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

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

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)

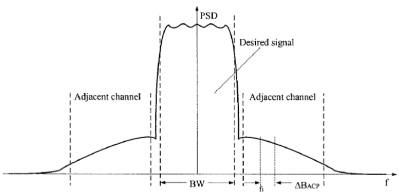
Systematic Transmitter Synthesis (II)

- 5.4 Adjacent and Alternate Channel Power
- 5.5 Noise Emissions
- 5.6 System design considerations
  - 5.6.1 Architecture selection
  - 5.6.2 Line-up, Gain Distribution
  - 5.6.3 TX AGC

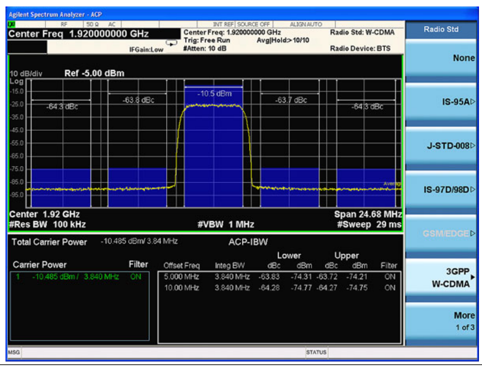
5.4 Adjacent and Alternate Channel Power

- Adjacent channel power ratio (ACPR)
- Spectral regrowth due to PA nonlinearity (intermodulation)
- Integrated in a channel

$$ACPR = \frac{\int_{f_1}^{f_1+\Delta B_{ACP}} SPD(f)\cdot df}{\int_{f_o-BW/2}^{f_o+BW/2} SPD(f)\cdot df}$$



Adjacent and Alternate Channel Power



Adjacent and Alternate Channel Power

- 5.4.1 Estimation using Low-Pass Model
  - Lowpass behavioral model of PA
    Complex envelope:

$$x(t) = A(t)\cos(\omega_0 t + \varphi(t))$$

$$y(t) = \underbrace{f(A(t))}_{\text{AM-AM}}\cos(\omega_0 t + \varphi(t) + \underbrace{g(A(t))}_{\text{AM-PM}})$$

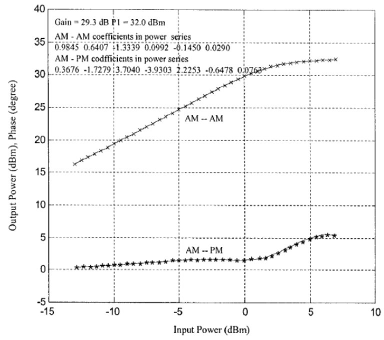
  - Using measured/simulated AM-AM and AM-PM characteristics, we can calculate

$$\tilde{y}(t) = f(A(t))e^{jg(A(t))}$$

where f and g can be approximated by Taylor series.

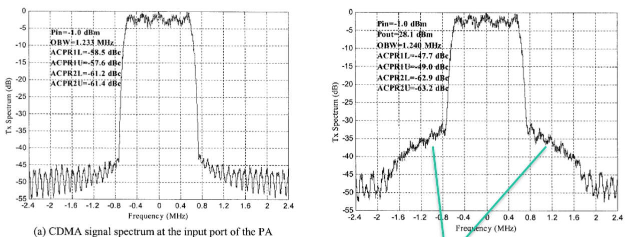
Which means we can not really calculate this with actual simple numbers or expressions

Example of AM-AM and AM—PM nonlinear PA characteristics



p. 336

Signal spectra at input and output of a PA

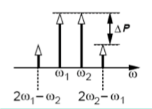


(a) CDMA signal spectrum at the input port of the PA

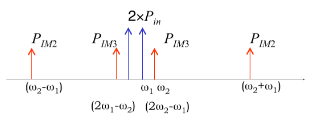
(b) CDMA signal spectrum at the output port of the PA

Spectral regrowth

Reminder about IP2 and IP3…



$$\boxed{IIP_3\big|_{dBm} = \frac{\Delta P\big|_{dB}}{2} + P_{in}\big|_{dBm}}$$



$$IIP_3 = P_{in} - IM_3/2 = P_{in} - (P_{IM3} - P_{in})/2 = (3P_{in} - P_{IM3})/2$$

$$IIP_2 = P_{in} - IM_2 = P_{in} - (P_{IM2} - P_{in}) = 2P_{in} - P_{IM2}$$

Add many tones at different frequency distances => spectral regrowth!

Adjacent and Alternate Channel Power

- 5.4.2 Calculation using multitone
  - Modulated signal modeled by two tones

$$P_{in}\big|_{dBm} = I_{2-tone,in} = I_{in} + 3dB$$

  - Regrowth by IM3 considered

$$IIP_3 = \frac{3I_{in} - P_{IM3}\big|_{dBm}}{2}$$

$$P_{IM3}^{out}\big|_{dBm} = 3(I_{2tone,in} - 3dB + G_{Tx}) - 2(IIP_3 + G_{Tx})$$

$$P_{IM3}^{out}\big|_{dBm} = 3(P_{Tx}\big|_{dBm} - 3dB) - 2OIP_3$$

One of several approximation for ACPR, see others at p. 339.

$$ACPR_{Adj} = \left(P_{IM3}^{out}\big|_{dBm} + 10\log\frac{\Delta BW_{ACP}}{BW}\right) - P_{Tx}\big|_{dBm} + C_0$$

Correction factor from PAR, e.g. for CDMA C_0 = 0.7.. 2dB, see (5.4.12) for details.

Adjacent and Alternate Channel Power

1

- Or required OIP_3 can be calculated

$$OIP_3 = \frac{3(P_{Tx}\big|_{dBm} - 3dB) - P_{IM3}^{out}\big|_{dBm}}{2}$$

$$P_{IM3}^{out}\big|_{dBm} = ACPR_{Adj} - 10\log\frac{\Delta BW_{ACP}}{BW} + P_{Tx}\big|_{dBm} + C_0$$

$$OIP_3 = P_{Tx}\big|_{dBm} - \frac{ACPR_{Adj}}{2} + 5\log\frac{\Delta BW_{ACP}}{BW} - 4.5dB + C_0/2$$

Example:
$ACPR_{Adj}$ = -45 dB
$ACPR_{Alt}$ = -60 dB
P_{TX} = 30 dBm
ΔBW_{ACP} = 30 kHz
BW = 1.25 MHz
C_0 = 2 dB
PAR = 3.8 dB

OIP_3 = 41dBm →-P_{1dB} ≈ -31dBm (OIP_3 - P_{1dB} >≈ 9.8 dB)
but P_{TX} = 30 dBm, PAPR = 3.8 dB, BO=3 dB (e.g.) => P_{1dB} = 36.7 dBm

For the alternate channel, the IM5 effect can be considered instead.

Adjacent/alternate channel power

- For the alternate channel, IM5 can be considered instead.

$$ACPR_{Alt} \cong \left(P_{IM5}^{out}\Big|_{dBm} + 10\log\frac{\Delta BW_{ACP}}{BW} \right) - P_{Tx}\Big|_{dBm}$$

$$IIP_5 = \frac{5(P_{Tx}|_{dBm} - 3) - P_{IM5}|_{dBm}}{4}$$

$$OIP_5 = P_{Tx}\Big|_{dBm} - \frac{ACPR_{Alt}}{4} + 2.5\log\frac{\Delta BW_{ACP}}{BW} - 3.75dB$$

Required OIP5, derived like OIP3

$$OIP_5 = 30 + \frac{60}{4} - 4 - 3.75 \cong 37dBm$$

D/A converter

- DAC with max swing → max SNR
- Number of bits → $SNR_Q >> SNR_{other}$
- Recall EVM² = 1/SNR, and EVMmax = 10% (typically req.)
- => SNR_{min} = 20 dB
- $SNR_Q = SNR_{min}$ + 20dB = 40dB
- SNR_Q = 6.02N +1.76 + 10logOSR

$$N = \frac{SNR_Q - 1.76 - 10\log OSR}{6.02}$$

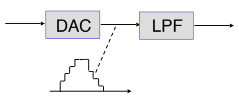
$$N = 6.35 - 1.66\log OSR$$

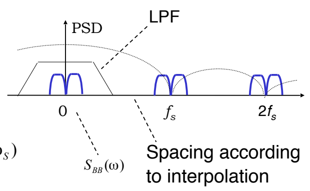
OSR = 4…8 → *N* = 6 (5)

More bits added to preserve pulse shaping. Typically 9-10 bits → linearity critical (SFDR), spurious emission must be avoided

D/A converter

- Sampling frequency → selectivity of the image reject filter
  OSR = 2… 8 is common



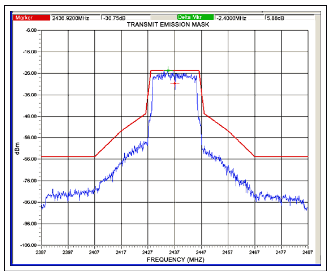


$$V_{DAC}(\omega) = \frac{\sin\omega T_S/2}{\omega T_S/2}\sum_k V_{BB}(\omega \pm k\omega_S)$$

- Predistortion 1/sinc can be introduced to compensate for DAC sinc shaping.

5.5 Noise Emissions

- TX leakage in to RX band
- Noise calculations (book)
- Spectrum mask



wlan 802.11g

Spectrum mask

- LTE UE (rel 10)

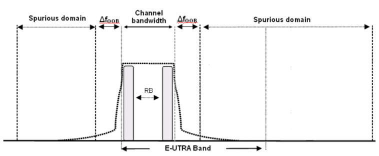
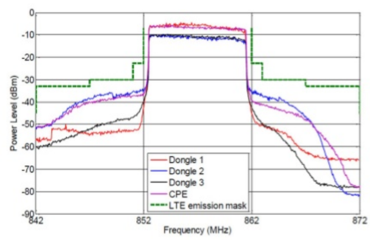


Table 6.6.2.1.1-1: General E-UTRA spectrum emission mask

Spectrum emission limit (dBm)/ Channel bandwidth							
Δf_{OOB} (MHz)	1.4 MHz	3.0 MHz	5 MHz	10 MHz	15 MHz	20 MHz	Measurement bandwidth
± 0-1	-10	-13	-15	-18	-20	-21	30 kHz
± 1-2.5	-10	-10	-10	-10	-10	-10	1 MHz
± 2.5-2.8	-25	-10	-10	-10	-10	-10	1 MHz
± 2.8-5		-10	-10	-10	-10	-10	1 MHz
± 5-6		-25	-13	-13	-13	-13	1 MHz
± 6-10			-25	-13	-13	-13	1 MHz
± 10-15				-25	-13	-13	1 MHz
± 15-20					-25	-13	1 MHz
± 20-25						-25	1 MHz

Noise Emissions

- LTE UE



Pmax: 23dBm
BW: 10MHz
50 RBs
Block C (UK)
@857MHz
16QAM

Source: Ofcom (August 2012)

Spectrum mask

- LTE UE (rel 10)

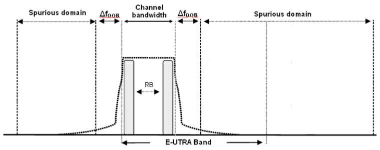


Table 6.6.3.1-2: Spurious emissions limits

Frequency Range	Maximum Level	Measurement Bandwidth
9 kHz ≤ f < 150 kHz	-36 dBm	1 kHz
150 kHz ≤ f < 30 MHz	-36 dBm	10 kHz
30 MHz ≤ f < 1000 MHz	-36 dBm	100 kHz
1 GHz ≤ f < 12.75 GHz	-30 dBm	1 MHz

5.6 System design considerations

- As for the RX: Good electrical performance, lower power consumption, low cost, small size.
  - 2/3 of current consumption in the total TRX.
  - 3/4 of TRX power in the TX.

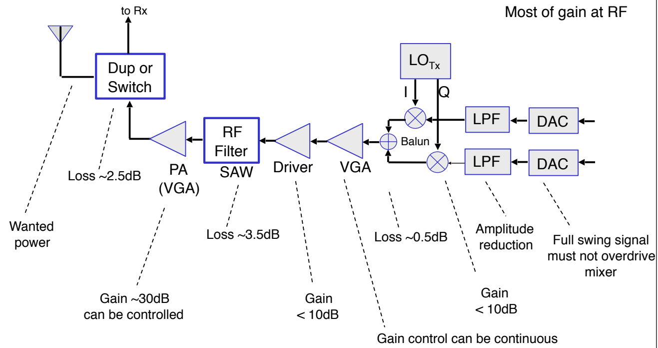
  => minimizing power especially important in the TX.

- As for the RX: Trade-off between a lot of parameters, e.g. higher linearity costs more current.
- As for the RX: Minimum requirements set by standards, with certain margins, typ. 3 dB at RT and 1.5 dB at max temp, frequency, voltage.

5.6.1 Architecture selection

- Direct conversion: Usually no IF channel filter used, so less advantage. Less spurious emission (no IF). More current since gain is rather in the RF.
- Today, power consumption/efficiency is very important (battery life for portable units, energy efficiency and heat removal for fixed units).
- A number of "new" architectures and PA operation to improve efficiency: Polar modulation (Envelope Tracking, ET), Outphasing, Doherty, Digital PA (DPA), PWM.

5.6.2 TX power and gain



5.6.2 TX power and gain

- Output power 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.

TX power and gain

- Example: P_{ARP} = 30 dBm

	Duplexer	PA	SAW	Driver	VGA	Balun	IQ_Mixer	
PowerGain	-2.5	28	-3.5	8		-1	7+3	
Power	30	32.5	4.5	8	0			$P_{in,mix}$

- Power at mixer input, 500 Ω input resistance assumed :

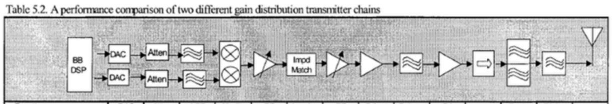
≤ 100 mV_{pp} @ mixer input

$$P_{in,mix} \le \frac{(V_{pp}/2)^2}{2R_{in}} = \frac{(0.1/2)^2}{2\cdot 500} = 0.25\times10^{-2} mW$$

$$P_{in,mix}\Big|_{dBm} \le -26dBm$$

Performance may vary with minor details in the TX chain

Table 5.2. A performance comparison of two different gain distribution transmitter chains



Function Block	DAC	Atten	LPF	Modltr Img-Rjc	RF VGA1	Impdnc Match	RF VGA2	Driver	Balun + SAW Fltr	PA	Directional Coupler	Duplx	Diplex	
(a) The first gain distribution with attenuation at the input														
Power Gain		**-8.00**	**0.00**	**5.00**	**4.17**	**-1.00**	**12.00**	**8.00**	**-4.00**	**27.00**	**0.40**	**-2.50**	**-0.50**	
Cascad Gain	0.00	-8.00	-8.00	-3.00	1.17	0.17	12.17	20.17	16.17	43.17	43.57	41.07	40.57	**40.57**
Pout (dBm)	-15.57	-23.57	-23.57	-18.57	-14.40	-15.40	-3.40	4.60	0.60	27.60	28.00	25.50	25.00	**25.00**
Vout (mVp-p)	2500.00	995.27	995.27	1769.86										
Rej @ Rx			20.00						30.00			42.00		
NF (dB) @ Rx Band	0.00	8.00	20.00	9.00	7.83	1.00	11.00	5.00	34.00	5.00	0.00	44.50	0.50	
Cascad NF @ Rx	0.00	8.00	28.00	37.00	37.80	37.81	38.55	38.55	39.81	41.70	41.70	51.42	51.87	**51.87**
OIP3(dBm)	1000.00	100.00	10.00	**6.00**	**11.17**	100.00	19.00	27.00	100.00	42.00	100.00	100.00	100.00	
Cascad OIP3	100.00	91.36	100.00	5.49	7.34	6.34	15.65	22.10	18.10	40.27	40.67	38.17	37.67	**37.67**
ACPR (dBc)	-59.73	-59.00	-59.00	-58.83	-58.53	-58.53	-57.57	-56.46	-56.46	-49.79	-49.79	-49.79	-49.79	**-49.79**
Noise in Rx band (dBm/Hz)	-153.37	-161.18	-173.28	-159.90	-154.95	-155.93	-143.21	-135.20	-167.96	-139.09	-138.69	-173.51	-173.56	**-173.56**
(b) The second gain distribution without attenuation at the input														
Power Gain		**0.00**	**0.00**	**5.00**	**0.17**	**-5.00**	**12.00**	**8.00**	**-4.00**	**27.00**	**0.40**	**-2.50**	**-0.50**	
Cascad Gain	0.00	0.00	0.00	5.00	5.17	0.17	12.17	20.17	16.17	43.17	43.57	41.07	40.57	**40.57**
Pout (dBm)	-15.57	-15.57	-15.57	-10.57	-10.40	-15.40	-3.40	4.60	0.60	27.60	28.00	25.50	25.00	**25.00**
Rej @ Rx		20.00							30.00			42.00		
NF (dB) @ Rx Band	0.00	20.00	2.00	9.00	9.83	5.00	16.00	5.00	34.00	5.00	0.00	44.50	0.50	
Cascad NF @ Rx	0.00	20.00	22.00	29.31	30.51	30.76	36.92	36.93	38.66	40.99	40.99	51.35	51.80	**51.80**
OIP3(dBm)	100.00	100.00	100.00	**10.00**	**18.17**	100.00	19.00	27.00	100.00	42.00	100.00	100.00	100.00	
Cascad OIP3	96.99	95.23	93.98	10.00	9.53	4.53	14.58	21.24	17.24	39.97	40.37	37.87	37.37	**37.37**
ACPR (dBc)	-59.00	-59.00	-59.00	-58.23	-58.00	-58.00	-56.86	-55.62	-55.62	-49.25	-49.25	-49.25	-49.25	**-49.25**
Noise in Rx band (dBm/Hz)	-153.37	-170.69	-169.64	-159.14	-157.89	-162.67	-144.81	-136.80	-169.10	-139.80	-139.40	-173.58	-173.62	**-173.62**

5.6.3 TX AGC

- GSM terminal: commands from base station, 2 dB gain/ power steps over 30 dB.
- CDMA: very fine steps of 0.25 - 1 dB.

Table 5.3. Maximum and minimum transmission power for mobile stations

Systems	Power Class	Nominal Maximum Power (dBm)	Nominal Minimum Power (dBm)	Dynamic Range (dB)	Power Control Method
AMPS	III	28	8	≥ 20	BS commands
CDMA 800	III	23	-50	≥ 73	Open and closed loops
CDMA 1900	II	23	-50	≥ 73	Open and closed loops
GSM 900	IV	33	5	≥ 28	BS commands
DCS 1800	I	30	0	≥ 30	BS commands
TDMA	III	28	8	≥ 20	BS commands
WCDMA	IV	21	-50	≥ 71	Open and closed loops

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