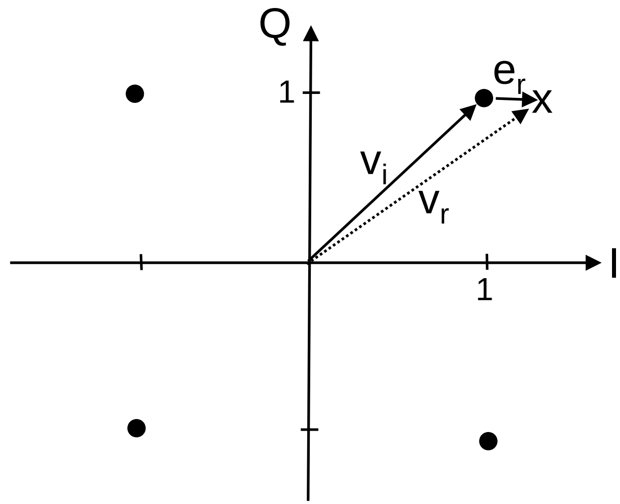
Receiver Radio System Calculations

an Example

- **Some important Rx system concepts/practice**
  - EVM
  - EVM impairments
  - Rx chain partition and budgeting
- **Calculating system requirements for a direct-conversion WCDMA receiver**
  - Sensitivity (NF)
  - Selectivity (ACR)
  - Dynamic range
  - Minimum gain
  - IP2
  - LNA IP3
  - I/Q down converter blocker IP3
- **References**

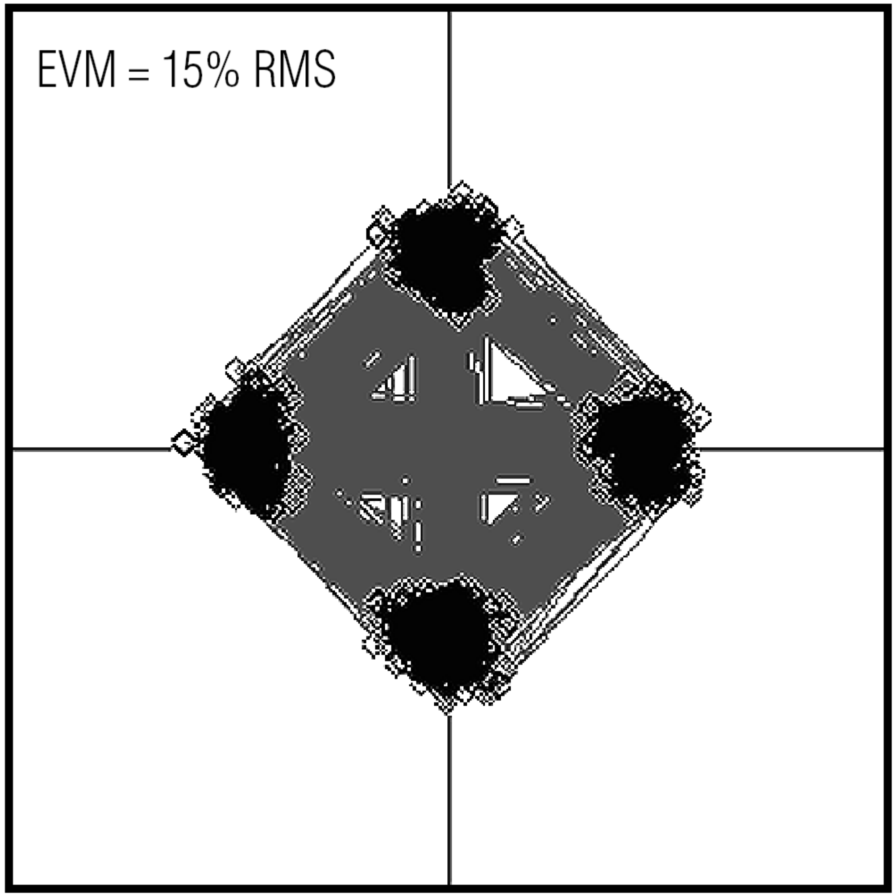
Error Vector Magnitude (EVM):



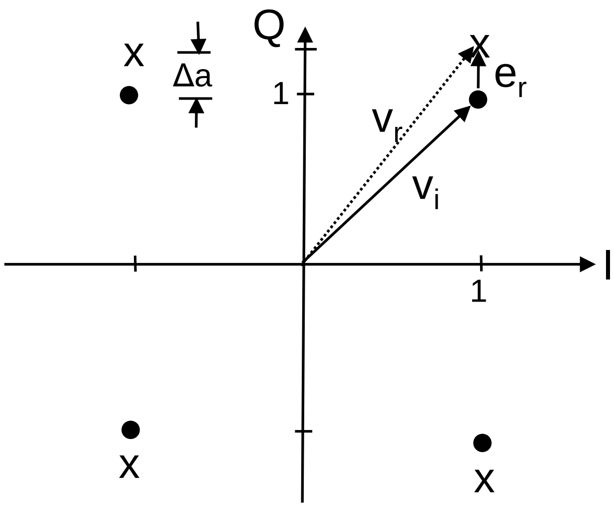
The WCDMA Rx modulation is QPSK. The none ideality of the receiver will cause the constellation to rotate or shift resulting in “blurry” or none tight constellation points or I/Q cross talk in the complex plane. The error vector magnitude (EVM) is the real time vector difference between an ideal vector in the complex plane and the real one averaged (rms) over several received packets (666.7µs for WCDMA system). There are several Rx parameters that affect the EVM, the most important of which are I/Q gain and phase mismatch, the LO phase noise, and the baseband filter.

Note: for a receiver EVM and SNR are related but they are not always equal.

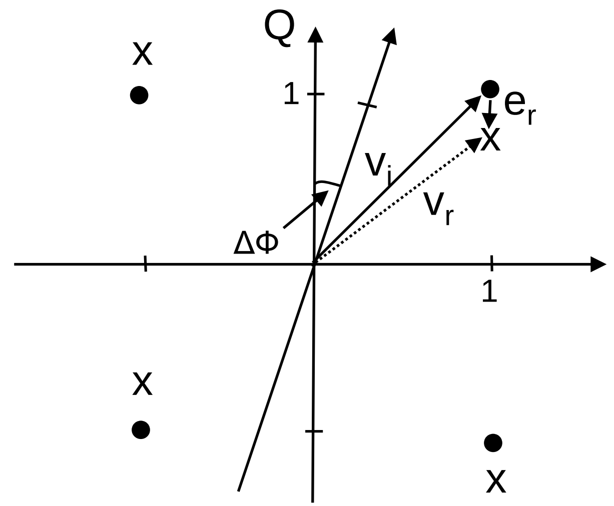
Measured EVM of an actual WCDMA Receive:



Effect of I/Q gain and phase imbalance on EVM:



I/Q gain imbalance case



I/Q phase imbalance case

The gain and phase imbalance results effectively in I/Q cross talk degrading the received signal to interference ratio. This can be calculated as follows. The ideal received signal with no I/Q imbalance can be written as:

$$v_{RF} = I(t)\cos(\omega_c t) - Q(t)\sin(\omega_c t), \quad \text{where we assume that}$$

$$I(t) = \cos(\omega_m t), \quad Q(t) = \sin(\omega_m t)$$

Effect of I/Q imbalance on EVM .. Cont':

The I/Q phase imbalance is mainly dominated by the LO quadrature. The LO can then be written as:

$$v_{LO,I}(t) = 2\cos(\omega_c t)\,;\;\; v_{LO,Q}(t) = 2\sin(\omega_c t - \delta\phi)$$

After mixing, the baseband output can be written as (with amplitude imbalance included)

$$v_{BB,I}(t) = LPF\left(v_{RF,I}(t).v_{LO,I}(t)\right) = \cos(\omega_m t)$$

$$v_{BB,Q}(t) = LPF\left(v_{RF,Q}(t).v_{LO,Q}(t)\right)\left(1+\delta a\right) =$$

$$\left(1+\delta a\right)\cos(\omega_m t)\sin(\delta\phi) + \left(1+\delta a\right)\sin(\omega_m t)\cos(\delta\phi)$$

Substituting the baseband results above into the RF signal equation and separating terms that are at the desired frequency of (ω_c + ω_m) and the residual side band signal at frequency (ω_c - ω_m). This results in

$$v_{RF,desired}(t) = \frac{\left(1+(1+\delta a)\cos(\delta\phi)\right)}{2}\cos(\omega_c+\omega_m)t - \frac{(1+\delta a)\sin(\delta\phi)}{2}\sin(\omega_c+\omega_m)t$$

$$v_{RF,residual\_SB}(t) = \frac{\left(1-(1+\delta a)\cos(\delta\phi)\right)}{2}\cos(\omega_c-\omega_m)t - \frac{(1+\delta a)\sin(\delta\phi)}{2}\sin(\omega_c-\omega_m)t$$

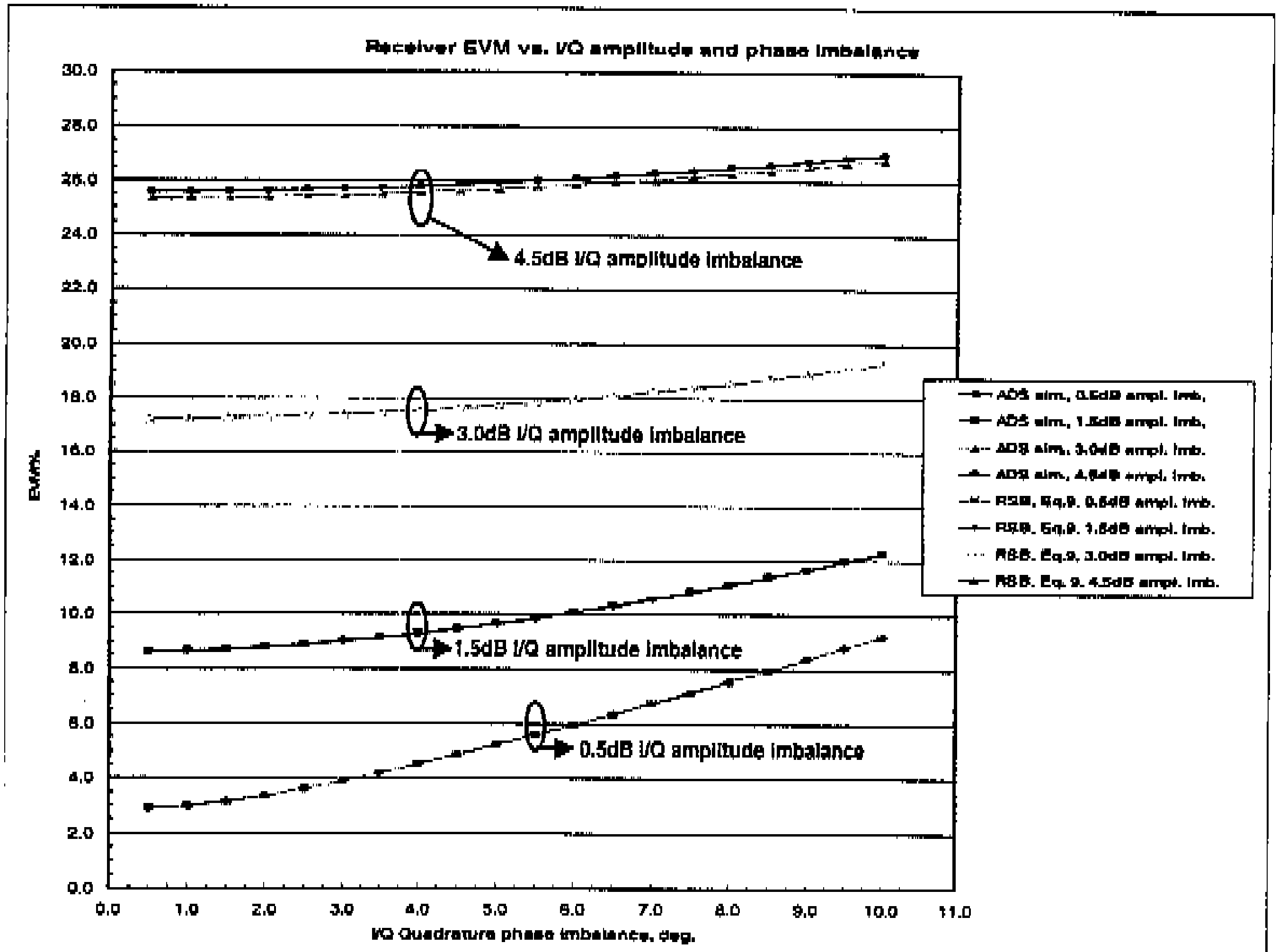
Effect of I/Q imbalance on EVM .. Cont':

As derived in a previous lecture, the mean square ratio between the desired to residual side band signal (IRR) can be written as:

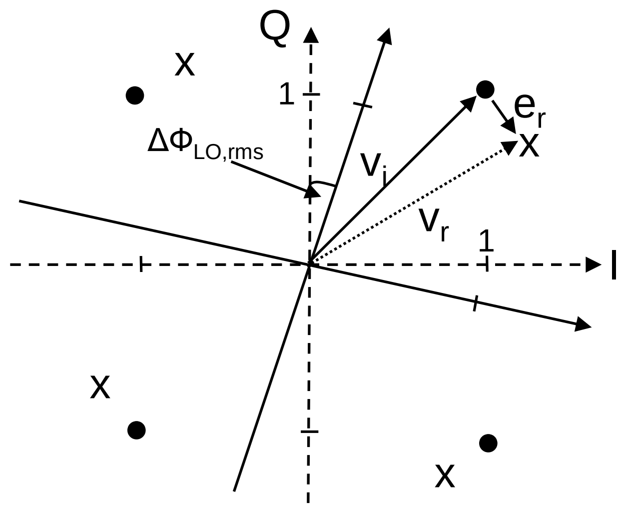
$$\frac{\overline{v_{RF,residual\_SB}^{\;2}}}{\overline{v_{RF,desired}^{\;2}}} = \frac{\left(1-(1+\delta a)\cos(\delta\phi)\right)^2 + \left((1+\delta a)\sin(\delta\phi)\right)^2}{\left(1+(1+\delta a)\cos(\delta\phi)\right)^2 + \left((1+\delta a)\sin(\delta\phi)\right)^2}$$

It turned out the ratio above is a good estimate of the effect of the I/Q mismatch to the receiver EVM. The effect of the EVM on the BER depends on the signal digital modulation. For the WCDMA QPSK, a 20% EVM is adequate for 10e-3 BER. A plot of the I/Q gain and phase mismatch and the resulting EVM is shown in the following graph. If we budget the maximum I/Q mismatch resulting in 10% EVM, this corresponds to1.5dB I/Q gain imbalance and 4° I/Q phase mismatch, which can easily be achieved by on-chip silicon implementation.

Effect of I/Q imbalance on EVM .. Cont':



Effect of LO phase noise on EVM:



Effect of LO phase noise on EVM

The LO phase noise integrated over the WCDMA receive signal bandwidth results in an rms phase error in time domain. Note that LO phase noise is random. In [2], an equation is derived to approximate the effect of LO phase noise on EVM as follows:

$$EVM_{\Delta\phi,LO} = \sqrt{2-2\cos(\Delta\phi_{LO,rms})}\ ; \qquad \text{where}\ \ \Delta\varphi_{LO,rms} = \sqrt{2\int_{100Hz}^{1.92MHz} \ell(f)\,df}$$

Effect of baseband filters on EVM:

The effect of baseband filter on EVM can be the result of two none idealities in filter response. First, the filter passband is not totally flat over the entire signal bandwidth due to filter passband ripple or droop. Second, the filter phase is not totally linear over the signal bandwidth resulting in group delay ripple. These two issues are set by the filter function and order which is set by the desired ACR.

Ref [3] derived an equation for the effect of baseband filter on EVM as follows:

$$EVM_{BB\_filter} = \sqrt{\Delta a_{rms}{}^2 + \left(\tan(\Delta\phi_{rms})\right)^2} \;;$$

where Δa_{rms} and $\Delta\phi_{rms}$ are the rms passband ripple, and the rms deviation from a linear phase, respectively.

Finally, the total receiver EVM is calculated by taking the root mean square value of all other sub EVM components as follows:

$$EVM_{RX} = \sqrt{EVM_{I/Q}^2 + EVM_{\Delta\phi,LO}^2 + EVM_{BB\_filter}^2}$$

A max value of 20% EVM can be tolerated in a WCDMA system which corresponds to 10e-3 BER. Note that such high EVM is acceptable because of the QPSK WCDMA signal. In some systems that use OFDM modulation, a much lower EVM (<3%) can be tolerated.

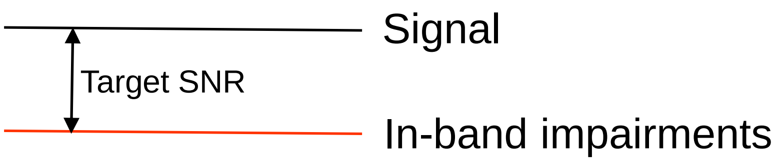
***Note:** a system simulator (such as Keysight ADS) can be used to simulate all impairments impact on EVM with actual modulated signals*

How to design a receiver based on target SNR?

It is all about budgeting SNR for impairments:

You need to differentiate between <u>in-band</u> and <u>out-of-band</u> impairments

For in-band impairments, you need to budget contributions to meet target SNR <u>at all conditions</u> and for all range of receiver input power:



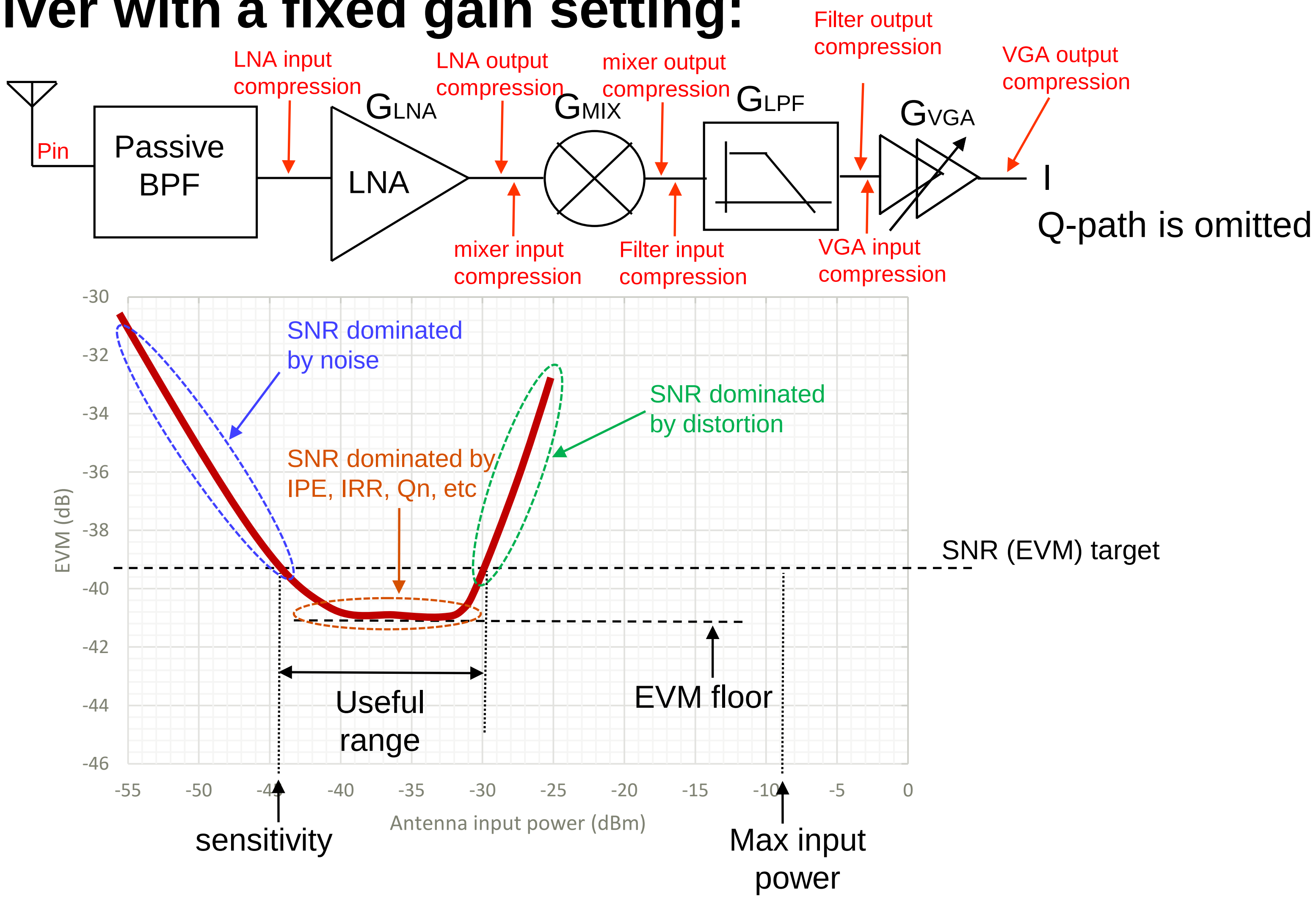
In-band impairments:

- thermal noise
- receiver IP2 and IP3 (in-band distortion)
- LO phase noise
- image
- ADC quantization noise
- other

SNR as a function of In-band impairments:

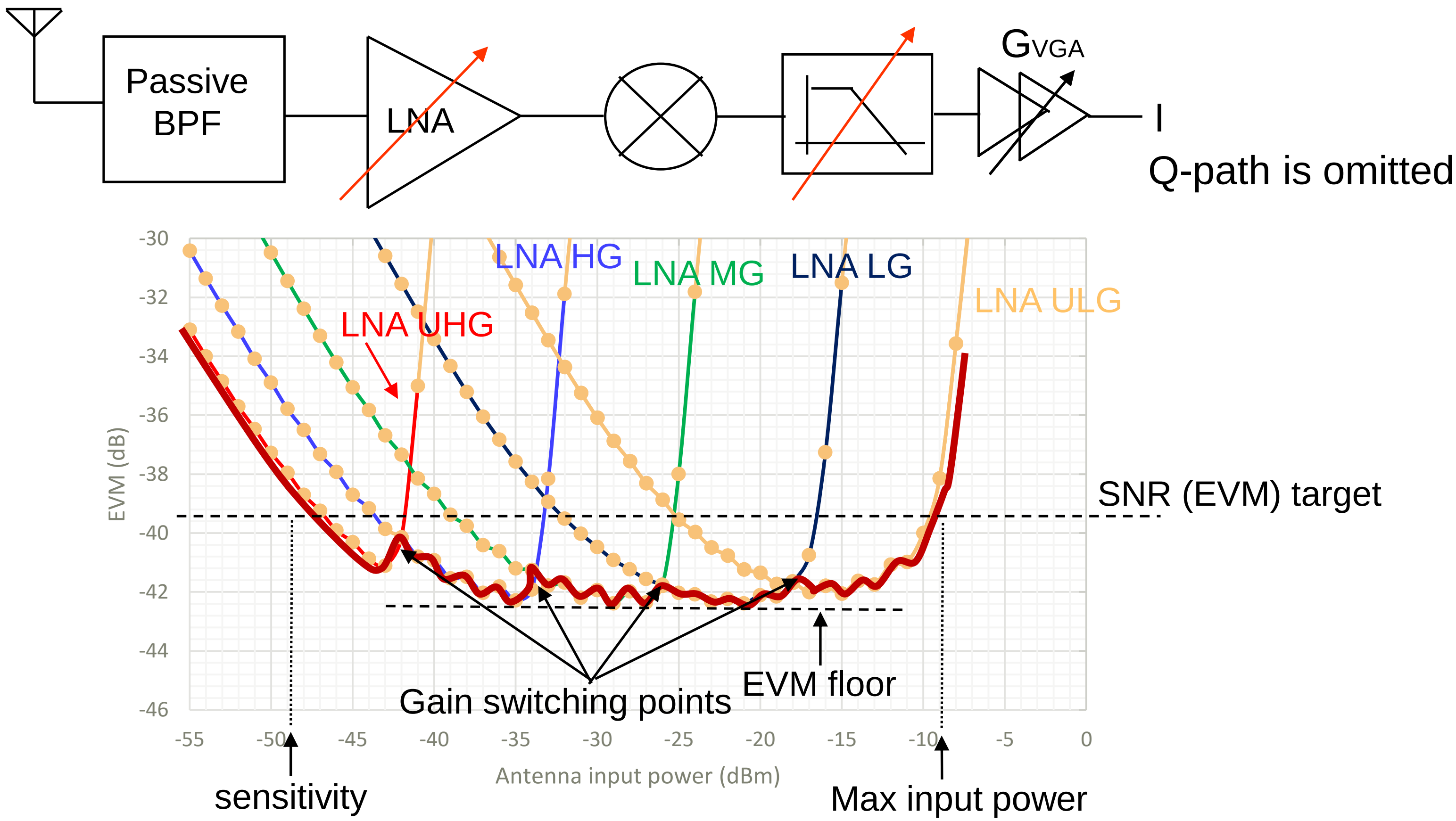
- **thermal noise:** for a given receiver gain, the SNR improves (dB by dB) as receive signal power increases.
- **receiver IP2 and in-band IP3 (in-band distortion):** for a given receiver gain, its IP3 is fixed and so SNR degrades by 2dB for each dB increase in receiver input power.
- **LO phase noise:** the LO phase noise is in dBc and so it is signal-level independent (stays constant as signal power changes).
- **Image:** image rejection is also in dBc and so is signal-level independent
- **ADC quantization noise:** in principle it is related to ADC FS and number of bits. However, its contribution to SNR varies a bit as a function of signal level. The reason it is “a bit” because AGC always tries to keep the input level to the ADC at a known set point relative to its Fs.

a receiver with a fixed gain setting:



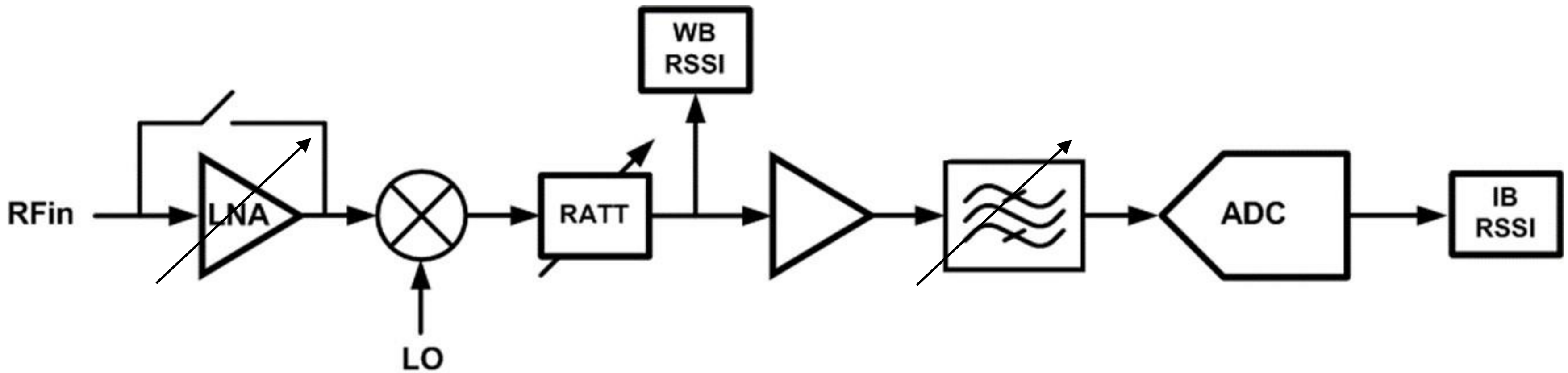
- Fixed-gain receiver covers only a limited range of input signal power
- Baseband gain adjustments help extend the range but limited by LNA/mix output (or input) compression.

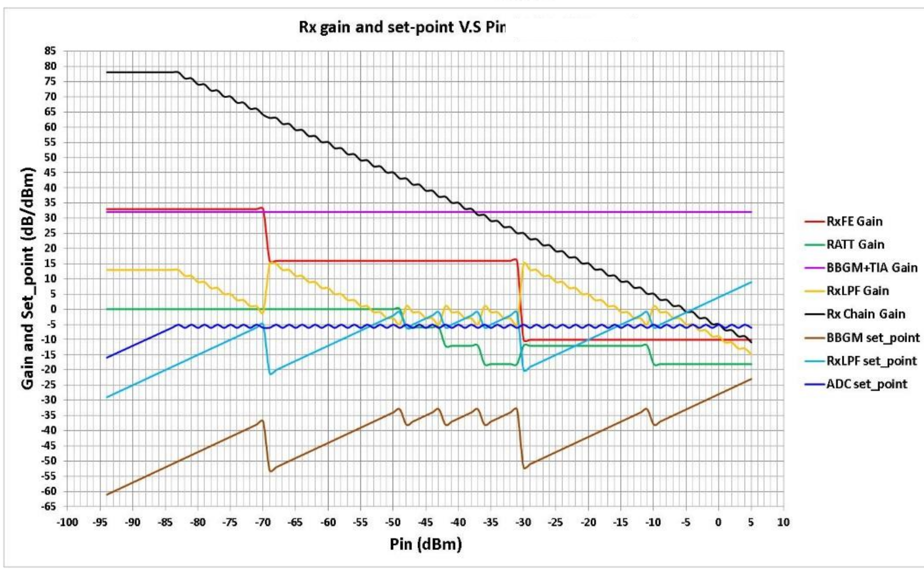
A multi-gain setting receiver:

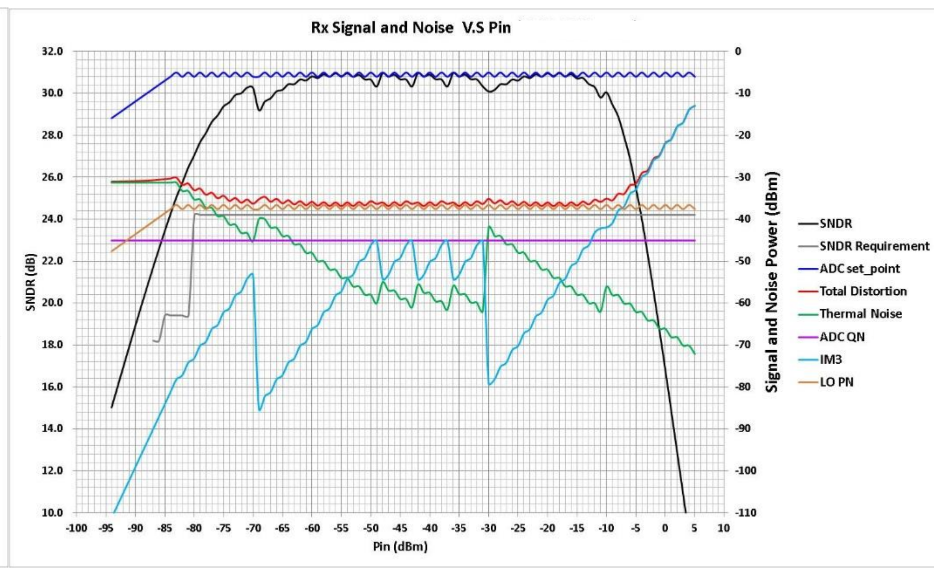


- Receiver with 5-gain LNA settings
- Number of gain-settings and performance of each gain setting (gain, gain-step, gain range, NF and linearity) is chosen to ensure a “smooth” SNR plot vs Pin. For relaxed EVM, fewer RFFE gain settings are needed

Gain and impairment adjustments to maintain SNR:

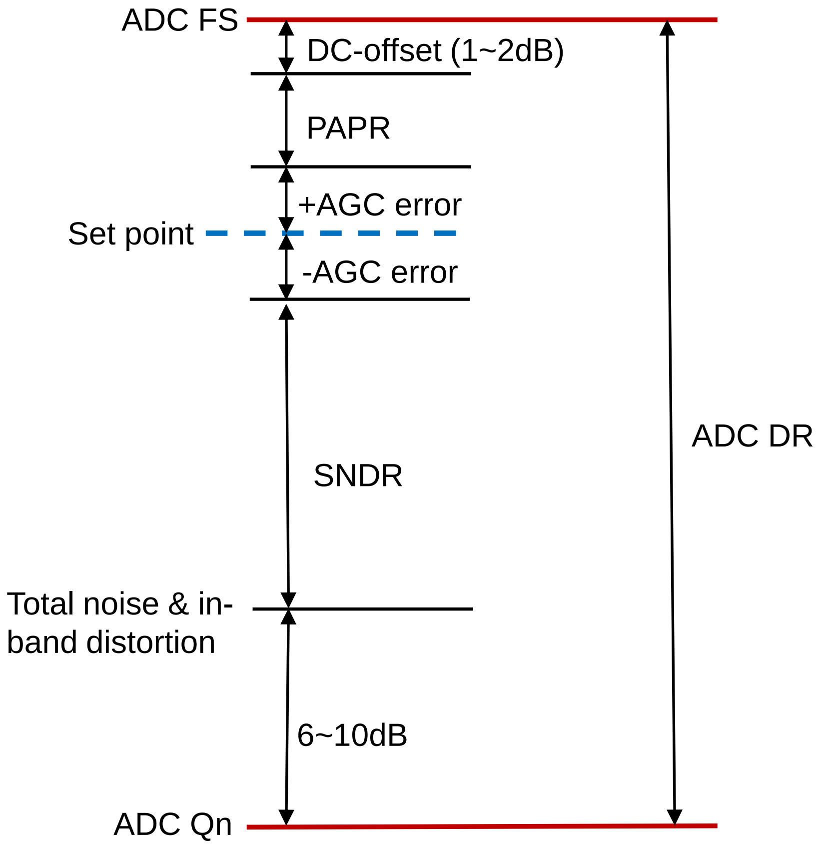






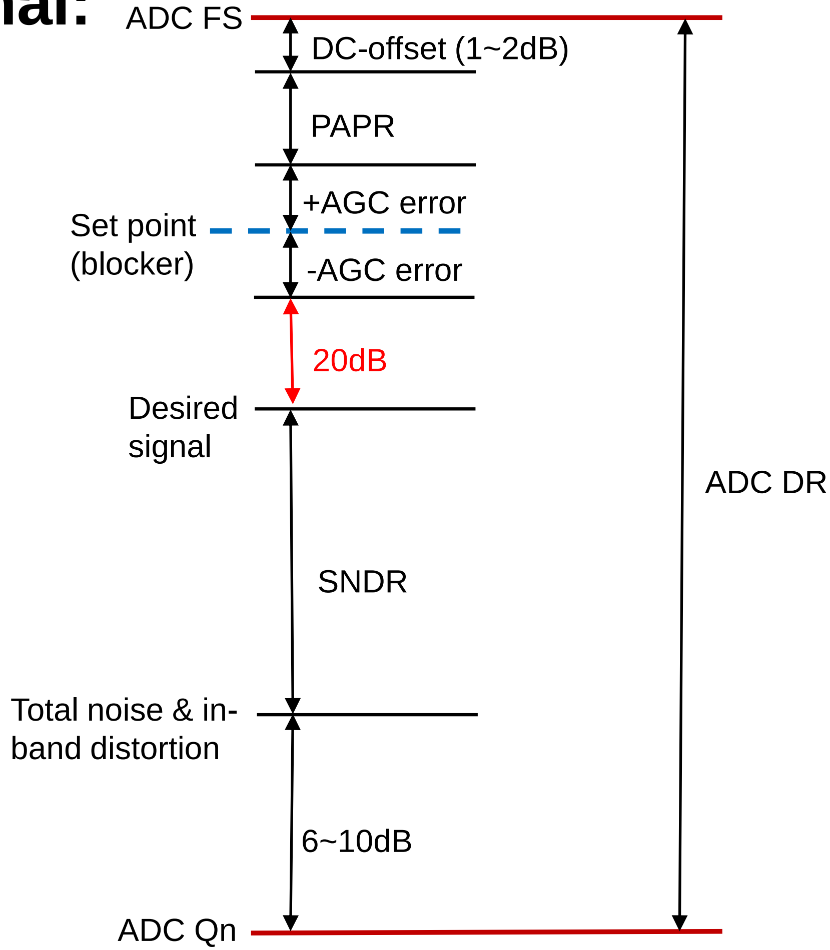
- Plot gain of each Rx stage over its gain range. Plot its noise and distortion
- Use spreadsheet to calculate cascaded Rx NF, linearity and other impairments such as LO phase noise and IRR, etc. Chose gain adjustment to keep signal close to ADC set point and SNR better than target over all Pin range

ADC dynamic range partition (no blocker case):



- Lowpass filter rejection, VGA gain range and ADC dynamic-range are all related. Trafeoff depends on best solution for lowest power consumption and die area
- A high-dynamic-range ADC requires less low-pass filtering rejection and can handle higher dynamic-range due to both in-band signal and blocker

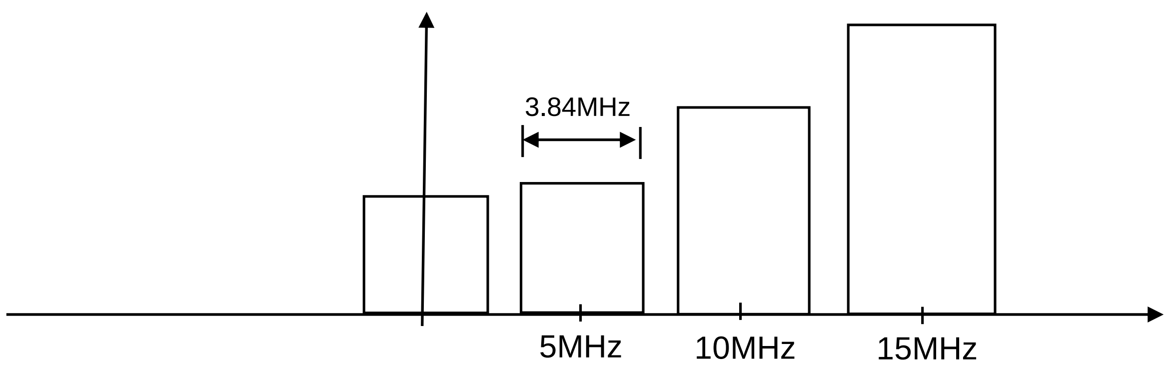
ADC dynamic range with blocker 20dB higher than desired signal:



- With an out-of-band blocker that is 20dB higher than signal, if you do not want to increase the filter rejection to reduce the blocker level to same level or below than that of the desired signal, the ADC dynamic range needs to increase by 20dB (in case of broadband blocker, the ADC sampling rate has to also increase to prevent blocker aliasing in-band)

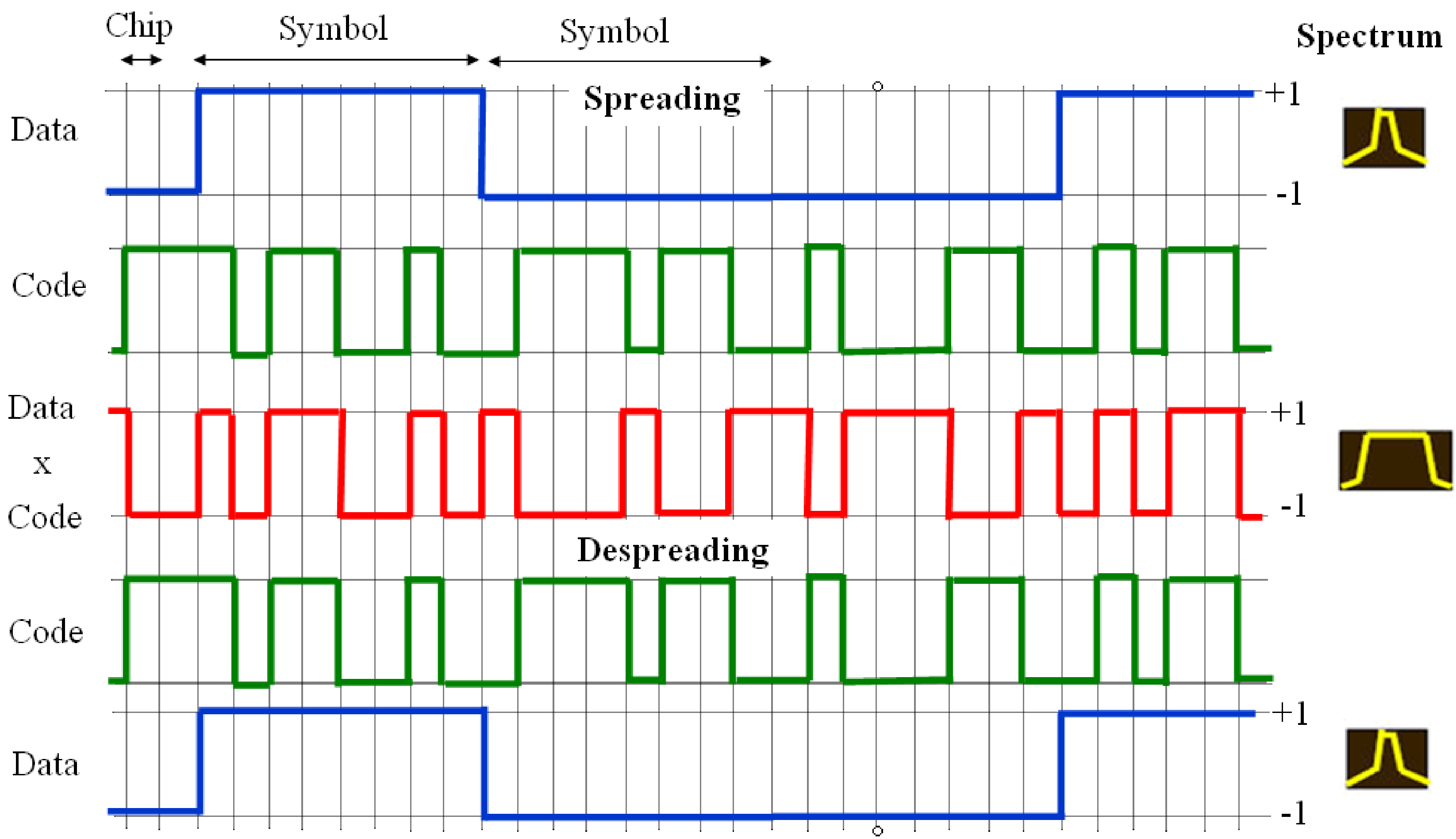
The WCDMA standard:

- Rx band: 2110-2170MHz; Tx band: 1920-1980MHz
- WCDMA channel bandwidth is 3.84MHz at RF, 1.92MHz at baseband for direct-conversion receiver
- modulation: QPSK for Rx; BPSK for Tx



- The 10MHz and 15MHz channel signals can be -56dBm and -44dBm, respectively, while desired signal is at -103dBm.

The Spread-spectrum system:

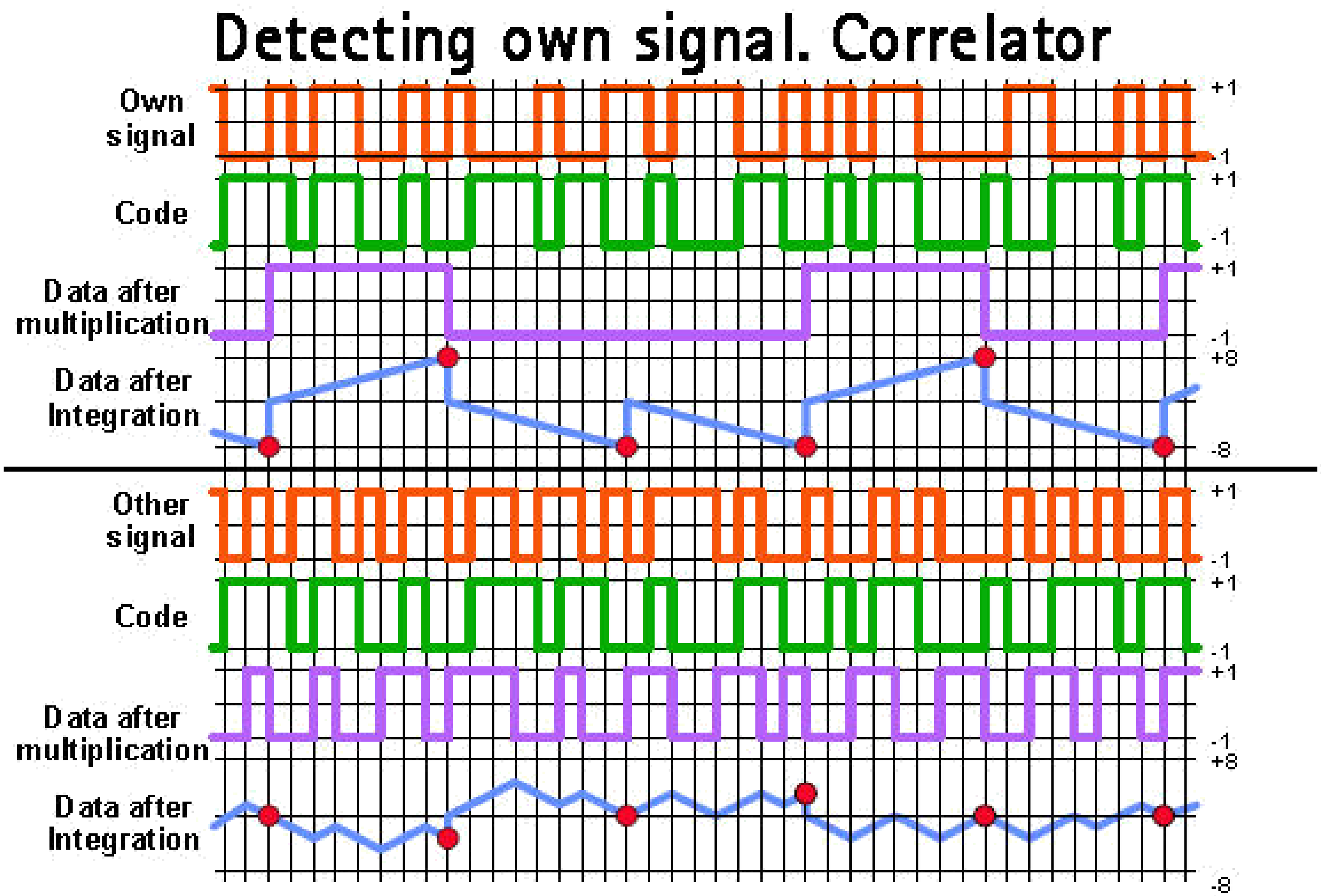


Courtesy Dr Timo Nihtilä

- each user is given a unique “random” code

The Spread-spectrum system:

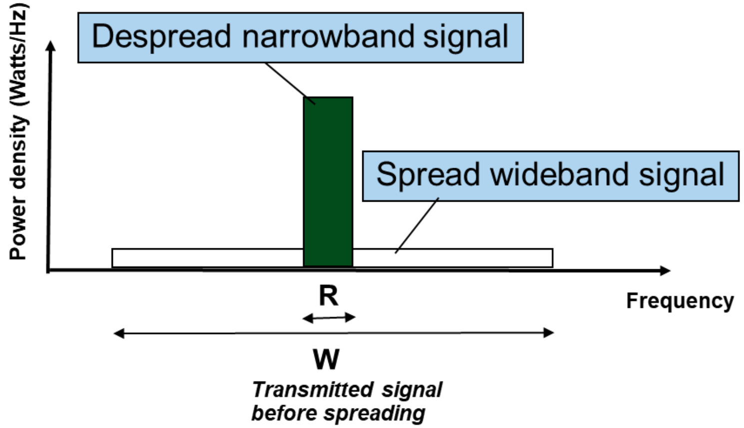
Courtesy Dr Timo Nihtilä

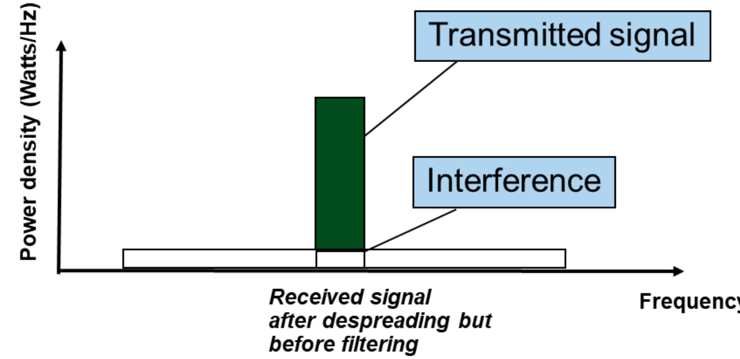


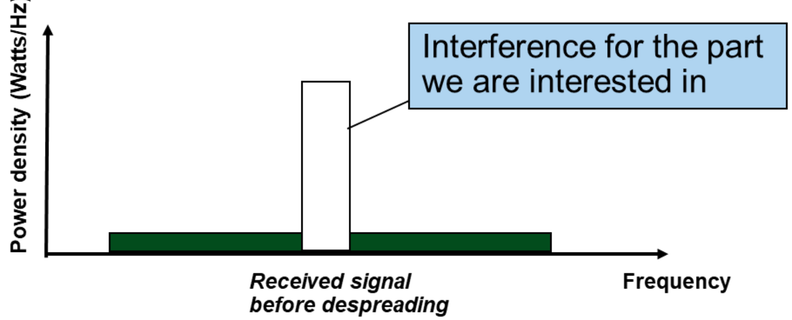
● multi-user can possibly use same band (interferer tolerant). Interferer can be treated as “white noise” if falls in-band because of the random code

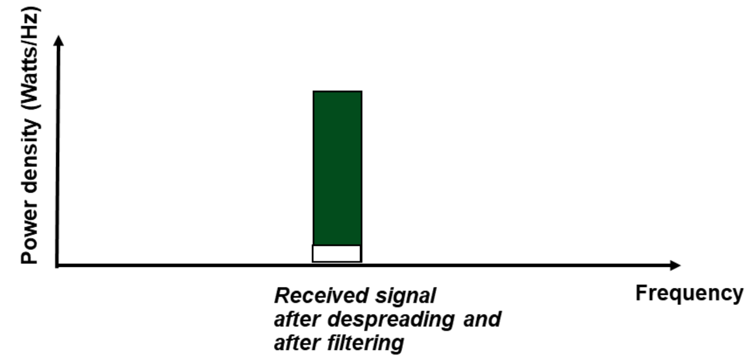
De-spreading and processing:

Courtesy Dr Timo Nihtilä



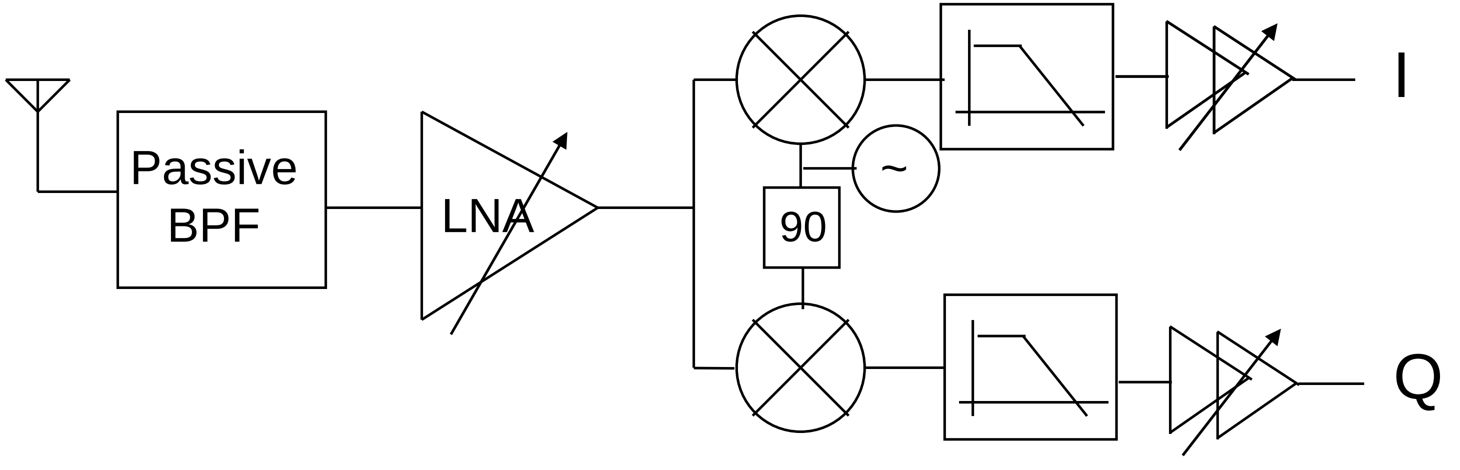






- after de-spreading, signal level increased (processing gain). For WCDMA this gain is 25dB (3.84MHz to 12.2kbps voice)

Direct-conversion WCDMA Rx:



Need to calculate:

- sensitivity, NF requirements
- selectivity, ACR requirements
- dynamic range and min gain, requirements
- receiver IP2 and IP3, requriements
- LO phase noise

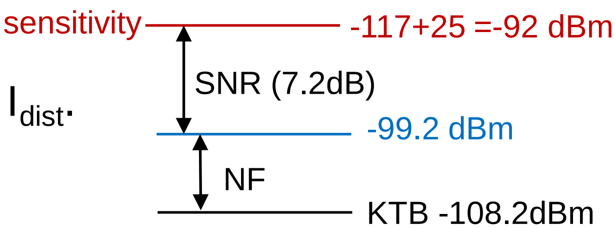
Calculating required Rx sensitivity (NF):

The 3GPP standard requires the S/N of 5.2dB still be met at an input signal level of -106.8dBm at the antenna. This corresponds to 10e-3 BER.

<u>-106.8dBm received signal power:</u>
Dedicated physical channel DPCH: **-117dBm**
Dedicated traffic channel DTCH, Dedicated control channel DCCH

After despreading and demodulation, the processing gain for a WCDMA is 25dB
$Eb/Ni = P_{DPCH} – I_{noise+dist} + Gp$, values in dB
Adding 2dB margin to the required S/N for temperature → target S/N is 5.2+2 = **7.2dB**

$7.2 = -117 + I_{noise+dist} +25 \rightarrow I_{noise+dist}$ = **-99.2dBm**



At sensitivity, SNR is dominated by noise only, so neglecting I_{dist}.

Thermal noise for the 3.84MHz signal bandwidth at RF is:
-174 + 10log(3.84e6) = **-108.2dBm**

So the required receiver NF at the antenna is -99.2 – (-108.2) = 9dB
With 2dB insertion loss of the duplexer and 1dB board loss → receiver **NF = 6dB**
We will design for 3dB margin over 3GPP spec → shoot for **3dB NF**!

Receiver gain and dynamic-range calculations:

$I_{desired-min}$ = -106.7dBm The 3GPP spec specifies the max received signal to be -25dBm. Therefore, the receiver must have a gain control range of:

AGC_{RX} = -25 – (-106.7) = 81.7dB

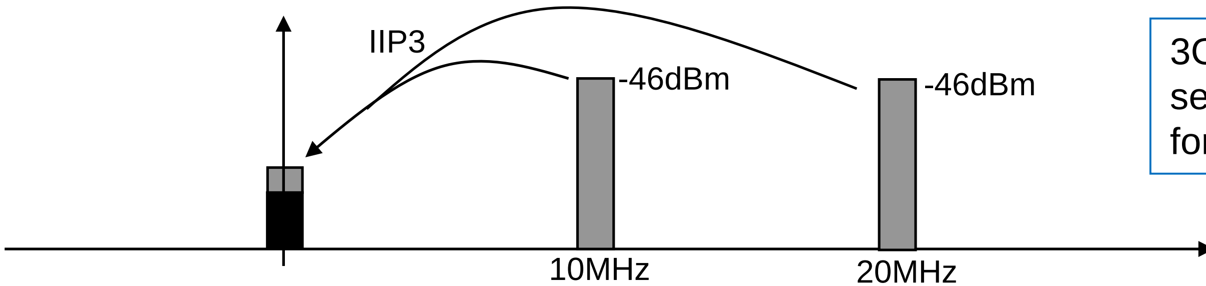
For this wide input signal dynamic range, and because of the relaxed SNR requirement, we will have only two-gain settings for the LNA; one is high-gain low NF, the other is low-gain with IP1dB compression ~10dB better than Pin_{max} or -15dBm

The ADC set point is set to 100mV rms ; → $I_{out-I/Q}$ = 110mV_{rms} or **-6dBm**

→ Receiver max gain = **100.7dB**.

If the LNA has a 22dB gain step, the I/Q demodulator (mixer and baseband) must have minimum of 60dB dynamic range (target is to shoot for 65dB to account for variation over process and temp).

Receiver inband blocker IP3 calculations:



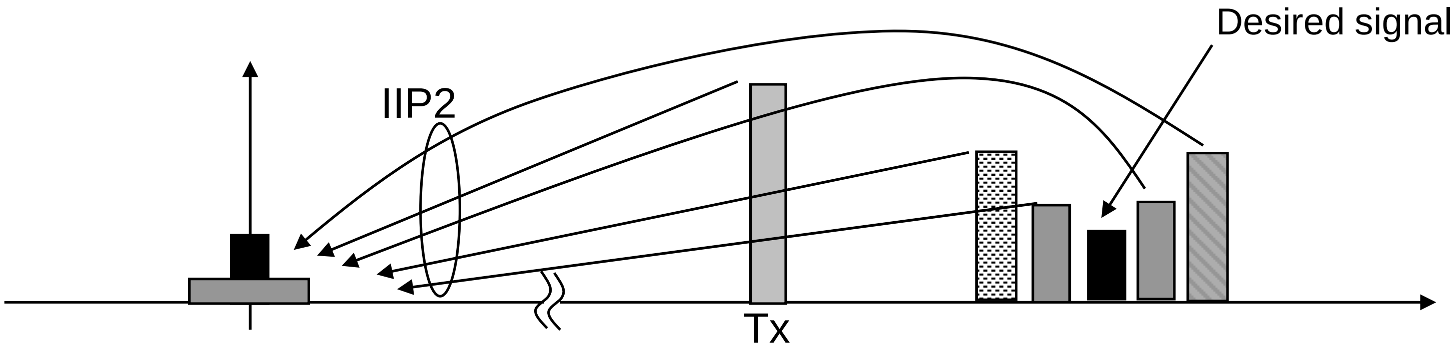
3GPP allows the receiver sensitivity to degrade by 3dB for blocker test case

$P_{noise+dist} \leq -96.2dBm$. Remember that $P_{noise} = -99.2dBm$
$P_{dist} = IM3 + IM2$

Assuming equal contribution between noise and distortion → $P_{dist} \leq -99.2dBm$
Assuming equal contribution between IM3 and IM2 results in an IM3 level of -102.2dBm.

Based on the above results, the inband block I IIP3 receiver requirement is
$IIP3_{10/20MHz}$ = 0.5(Pin – IM3) + Pin = 0.5(-46 + 102.2) -46 = **-17.9dBm** at the antenna**.**
Note that this IP3 is dominated by the I/Q demodulator. With 2dB insertion loss in the duplexer and 16dB gain in the LNA, the required I/Q demodulator IIP3 is **-3.9dBm**.

Receiver in-band blocker IP2 calculations:

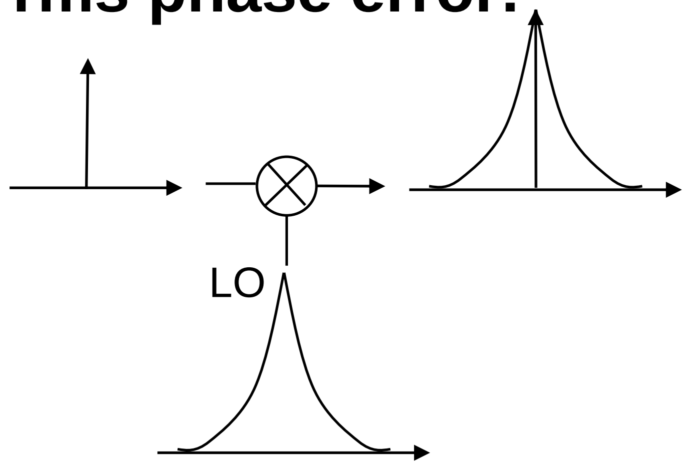


It was calculated that the budget for the 10MHz and 15MHz in-band blocker IM2 is -102.2dBm each. Therefore, the IP2 requirement for each of these blockers can be Calculated as:

$IIP2_{10MHz} = (P_{10MHz} - IM2_{10MHz}) + P_{10MHz} = -56 + 102.2 - 56 =$ **-10.8dBm**
$IIP2_{15MHz} = (P_{15MHz} - IM2_{15MHz}) + P_{15MHz} = -44 + 102.2 - 44 =$ **+13.2dBm**

With LNA output AC coupled to mixer input, the receiver IP2 is limited by that of the I/Q demodulator. With 16dB LNA gain, the required **IIP2** for the I/Q demodulator at 10MHz and 15MHz is **+5.2dBm** and **+29.2dBm**, respectively.

LO integrated rms phase error:

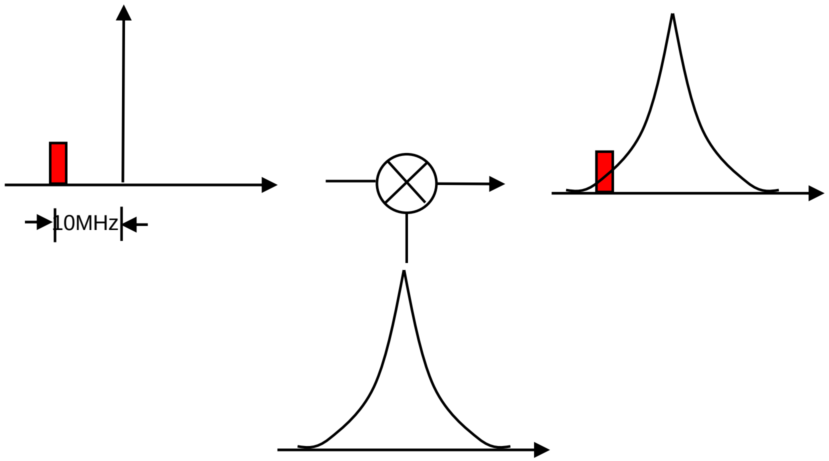


The LO phase noise gets convolved with the incoming signal spectrum (regardless of its frequency) causing its phase noise to degrade the signal inband SNR. In order for this degradation to be negligible, it needs to be at least 15dB below the target SNR for a particular modulation. For our case it means 7.2dB + 15dB = 22.2dBc. This translates into a carrier to noise ratio (C/N) of:

$$\mathbf{C/N} = 20log(IPE) = -22.2 \rightarrow IPE = 0.078rad = 4.5^{\circ}$$

This phase noise is integrated from ~1kHz to 1.92MHz (double side) as shown earlier

VCO/LO phase noise calculations:



10MHz offset jammer will result in VCO phase noise reciprocal mixing that aliases over the desired signal band degrading the S/N. The required min LO phase noise can be calculated as follows.

$P_{noise+dist} \leq -96.2dBm$

We want the S/N reduction due to LO phase noise reciprocal mixing to be <0.1dB.

$-96.2 + P_{\Phi N} = -96.1 \rightarrow P_{\Phi N} = -112.5dBm$

This is the integration power of LO phase noise from 8.08MHz to 11.92MHz (the band of the 10MHz offset LO reciprocal mixing profile that aliases over the 3.84MHz desired WCDMA signal).

VCO/LO phase noise calculations … cont':

Therefore the required LO phase noise can be calculated as follows.

$$10\log\int_{8.08M}^{11.92M}\frac{K}{f^2}df = -112.5\text{dBm} \quad \Rightarrow K = 1.41\times10^{-4}\,\text{Hz}$$

$$10\log\left(\frac{K}{f^2}\right)@10\text{MHz} = 10\log\left(\frac{1.41\times10^{-4}}{\left(10\times10^6\right)^2}\right) = -178.5\text{dBm/Hz}$$

With the 10MHz offset jammer at -46dBm level, the required LO phase noise can be expressed in dBc/Hz at 10MHz offset as:

-178 – (-46) = -132.5dBc/Hz @ 10MHz offset

This is the min LO phase noise requirement. We will shoot for -136dBc/Hz typical value.

- ***Note**: back to the budgeting issue, if this LO phase noise is shown to impact current consumption, it can be relaxed but then the IP2/IP3 specs will need to be tightened so the overall SNR is still met.*

Adjacent channel rejection calculation:

This ACR is related to how much filter rejection and ADC dynamic/range is best. In this analysis we are going to assume the filter is designed to attenuate blockers to a level not to impact in-band SNR due to ADC aliasing (to relax ADC dynamic range). You can relax the filter rejection by increasing the ADC dynamic range (and its sampling rate to prevent aliasing) as discussed earlier

$I_{desired}$ = -92.7dBm ; I_{DPCH} = **-103dBm** for desired signal

I_{5MHz} = **-52dBm**

Signal level is -103dBm, which is 14dB above the sensitivity level (-117dBm). If we assume a Nyquist ADC, We can then assume that the signal corruption is mainly due to adjacent signal power folding (aliasing).

Required S/N = 7.2dB to achieve 10e-3 BER.
Eb/Ni = PDPCH – $I_{noise+dist}$ + Gp , values in dB

7.2 = -103 – $I_{noise+dist}$ + 25 → $I_{noise+dist}$ = **-85dBm**

With the 5MHz adjacent signal level is -52dBm → required minimum ACR is:

-52 – (-85) = **33dB**

We will shoot for 36dB min rejection (3dB margin).

10MHz and 15MHz channel rejection calculation:

$I_{desired}$ = -103.7dBm ; I_{DPCH} = **-114dBm** for desired signal

I_{10MHz} = **-56dBm ;** I_{15MHz} = **-44dBm**

Required S/N = 7.2dB to achieve 10e-3 BER.
Eb/Ni = PDPCH – $I_{noise+dist}$ + Gp , values in dB

7.2 = -114 – $I_{noise+dist}$ + 25 → $I_{noise+dist}$ = **-96.2dBm**

Signal level is -114dBm, which is 3dB above the sensitivity level (-117dBm). The signal corruption can be due to 10/15MHz signal power aliasing, noise and IM2/IM3. Assuming equal contributions of all four factors: -96.2 - 10log(4) = **-102.2dBm**

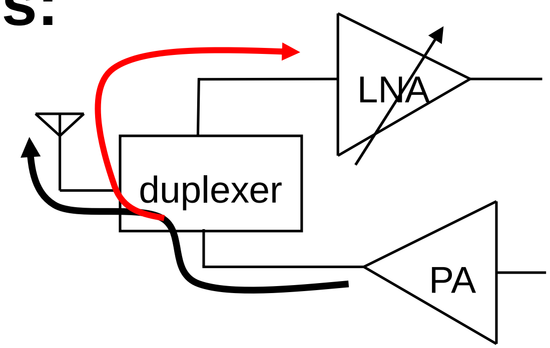
With the 10MHz level is -56dBm → required minimum rejection is:

-56 – (-102.2) = **46dB**

With the 15MHz level is -44dBm → required minimum rejection is:
-44 – (-102.2) = **58dB**

We will plan for 3dB margin → rejection is 49dB and 61dB minimum for 10MHz and 15MHz signals, respectively. Note this rejection is integrated over the entire 3.84MHz WCDMA signal bandwidth.

IM2 due to Tx in FDD systems; Receiver out-of-band IP2 calculations:



The WCDMA is a full duplex system, which means both Tx and Rx are ON at the same time. The 3GPP spec calls for max PA output power of **+27dBm**. Due to finite Tx→Rx isolation inside the duplexer, significant Tx power will leak to the LNA input. A typical WCDMA duplexer has around **50dB** min Tx→Rx isolation. This means the Tx leakage power to the LNA input is:

$P_{TX\text{-}leakage}$ = 27 – 50 = -23dBm ← sets LNA compression (6dB better so $P1dB_{LNA}$=-15dBm min)

Due to second-order nonlinearity, the receiver will detect the envelope of the non-constant envelope leakage transmit signal and convert it to baseband at twice the envelop signal bandwidth. This can be seen as follows

$$[m_{Tx}(t)\cos(\omega_{Tx}t)]^2 = \frac{1}{2}m_{Tx}(t)^2 + \frac{1}{2}m_{Tx}(t)^2\cos(2\omega_{Tx}t)$$

Receiver out-of-band IP2 calculations … cont':

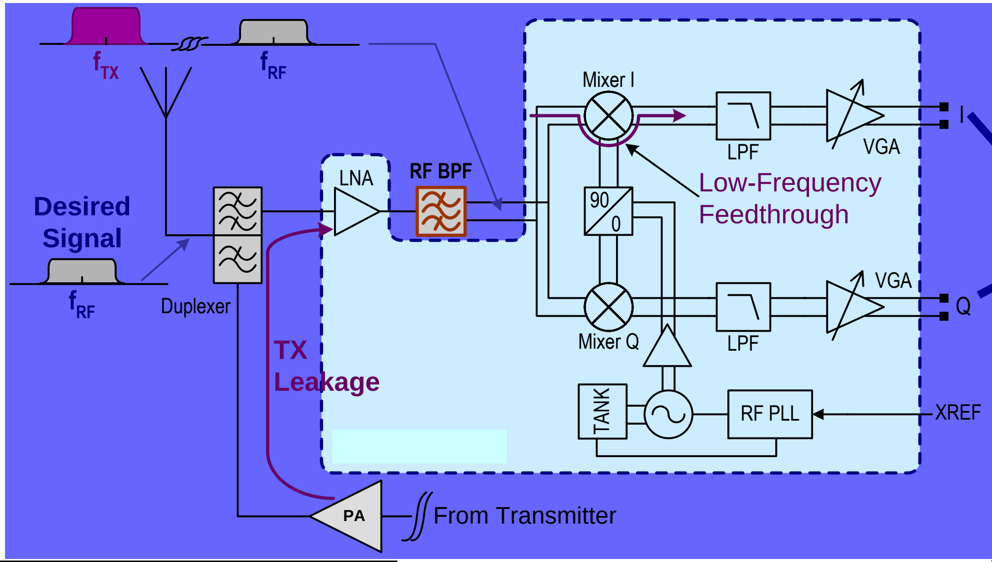
At sensitivity, the maximum acceptable noise+distortion power is -99.2dBm. The IM2 resulting from the Tx leakage power should be at least 10dB lower than this. Therefore, **$IM2_{Tx}$ = -109.2dBm**. With **$P_{TX\text{-}leakage}$ = -23dBm**, the IP2 can be calculated as:

$IIP2 = (P_{TX\text{-}leakage} – IM2_{Tx}) + P_{TX\text{-}leakage} = -23 + 109.2 – 23 =$ **+63dBm**

Adding 3dB margin results in a required IIP2 of **+66dBm** at the LNA input. With 16dB typical LNA power gain, the required IP2 of the I/Q downconverter is **+82dBm**! This is unfeasible with on-chip techniques known today with reasonable current and no Trimming/calibrations. So what to do??

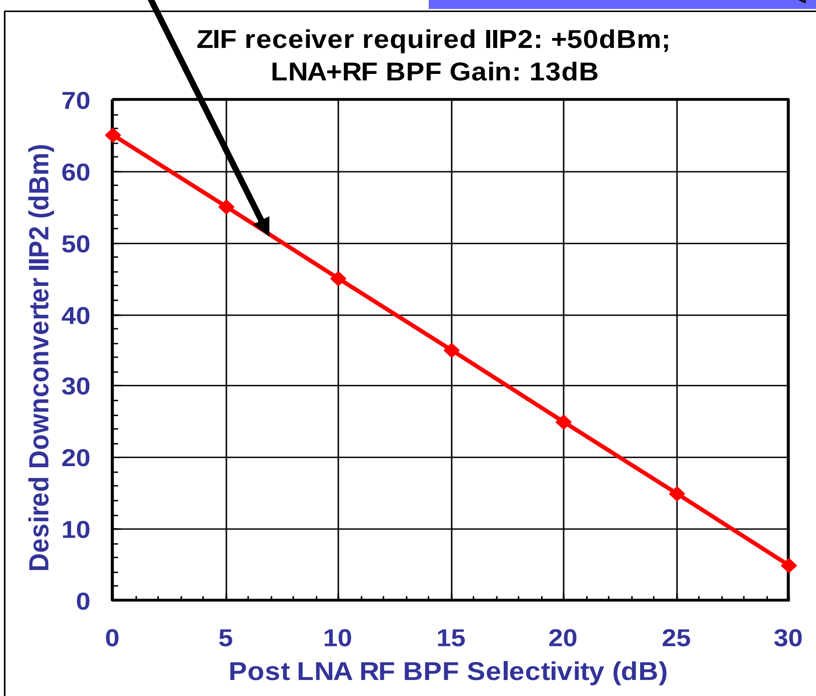
1) Modify the architecture by inserting an off-chip SAW filter at the LNA output to filter out the Tx power before it reaches the mixer. With min WCDMA SAW filter rejection at the Tx band of **55dB**, the I/Q down converter IP2 is relaxed to **+26dBm**. A single-ended to differential output SAW filter can be used to drive the mixer differentially without the need of a balun. Also a differential topology will be used for the down converter to ensure highest possible IP2
2) The LNA IP2 can be completely removed from the picture if the output of the LNA is AC coupled to the mixer input, hence, filter out the IM2 generated in the LNA before it reaches the mixer input

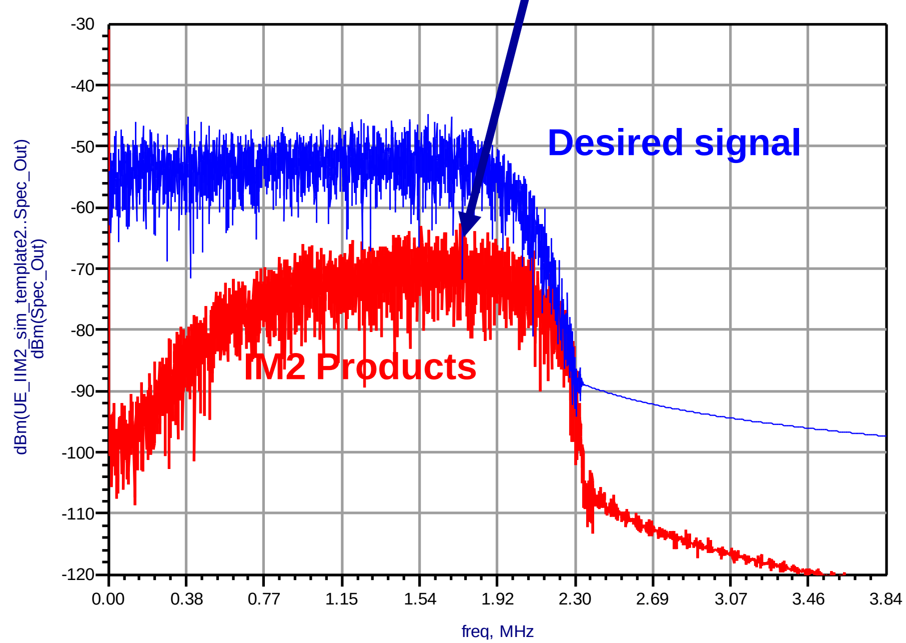
Receiver IP2 requirement vs. SAW-filter rejection



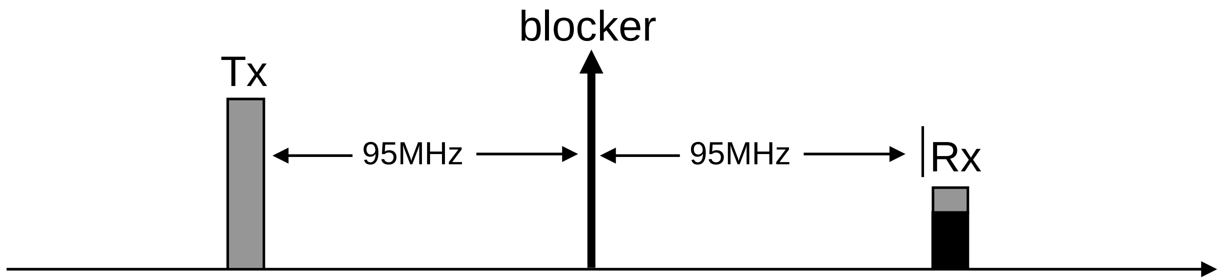
With actual WCDMA signal, required IP2 is smaller than calculated using CW tones
→ You can decide to remove SAW after LNA but rely on IP2 calibration (need guaranteed +65dBm IIP2 for the I/Q converter per the plots below)

Relaxation of ZIF mixer IIP2 versus post-LNA RF BPF Selectivity at TX leakage frequency offset





Receiver IP3 calculations:



The Tx leakage power can mix with a jammer midway between the Tx and Rx bands and generate an IM3 interferer falling right on the desired signal. For the WCDMA 2110-2170MHz band, the jammer can fall into one of the following three known bands:

Band I: 2010-2025MHz with max power level of -15dBm at the antenna
Band II: 2025-2050MHz with max power level of -30dBm at the antenna
Band III: 2050-2075MHz with max power level of -44dBm at the antenna

The duplexer provides rejection of 30dB, 17dB and 3dB, at the above 3 bands, respectively. The Tx leakage power is -27dBm at LNA input and the max acceptable noise+distortion power is -96.2dBm at the antenna. With 2dB insertion loss inside the duplexer, the max acceptable noise+distortion power at the LNA input is -98.2dBm. Assuming equal contribution between noise and **IM3** distortion, the max acceptable distortion power is then **-101.2dBm**.

Receiver IP3 calculations … cont':

The receiver IP3 can be then calculated for each band as follows:

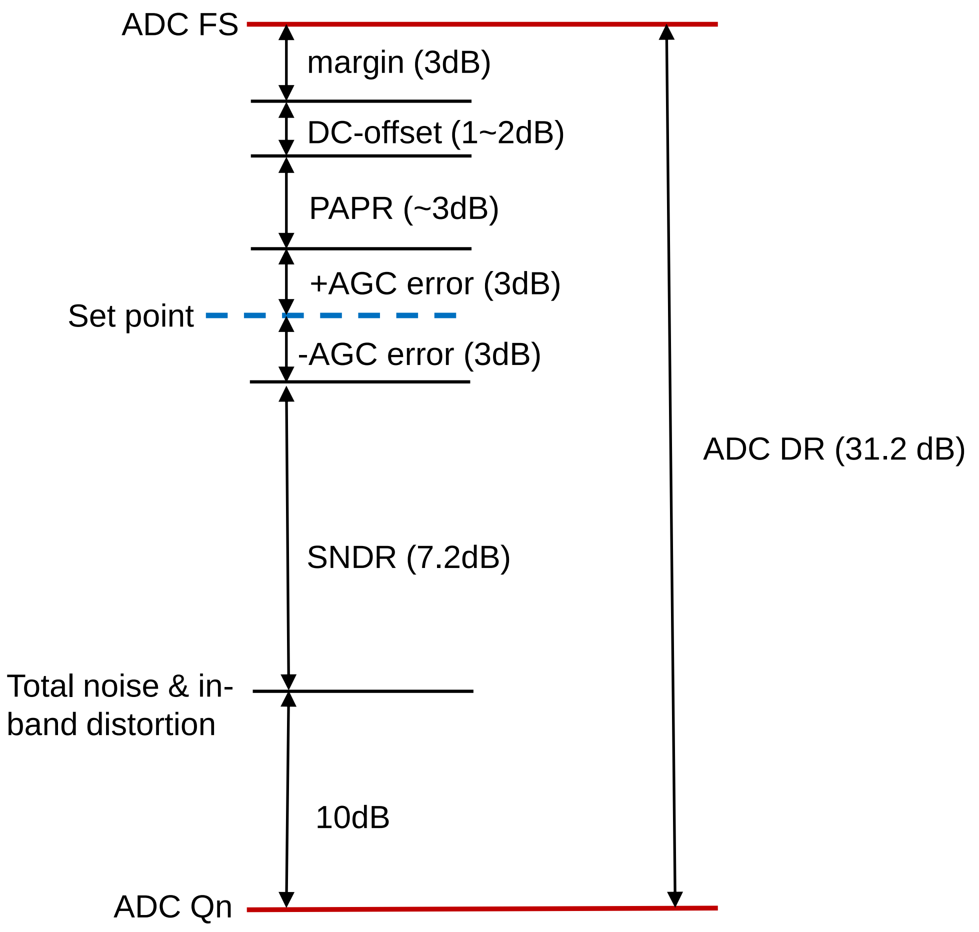
Band I: IIP3 = 0.5(Pin – IM3) + Pin , where Pin is the power per tone. With Tx tone at -27dBm and the Band I jammer is at -45dBm at the LNA input (duplexer rejection to Band I jammer is 30dB), the equivalent per tone power can be calculated as follows. Since the IM3 spur is the result of $2f_{Blocker} + f_{Tx}$, therefore, the equivalent Pin = $(2P_{Blocker} + P_{Tx})/3$ = (2*(-45) -27)/3 = -39dBm

Based on the above results, the Band-I IIP3 receiver requirement is **$IIP3_{Band\ I}$** = 0.5(-39 + 101.2) + -39 = -7.9dBm. Adding 4dB margin → **$IIP3_{Band\ I}$** = **-3.9dBm**

Note that this IP3 is dominated by the LNA since the transmit power is highly attenuated by the added SAW filter at the LNA output.

Following similar calculations for the band II and III, the IIP3 is calculated for these bands as -9.9dBm. It is obvious the IIP3 is set by the Band-I IP3 blocker spec.

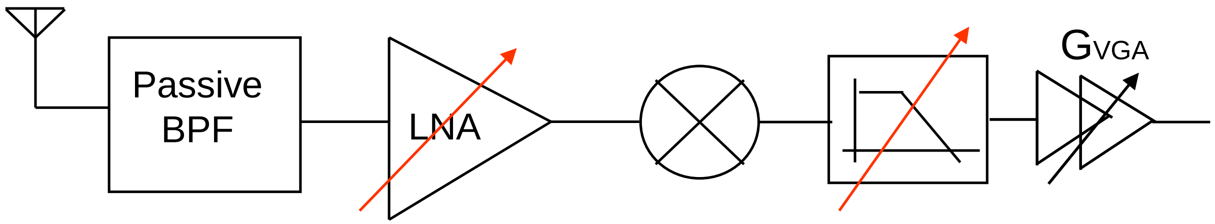
ADC dynamic range partition



- Total required ADC dynamic range is only 31.2dB (blockers are filtered out by LPF)

→ 5bits EnoB is enough. We will add one more bit for margin → 6bits ADC

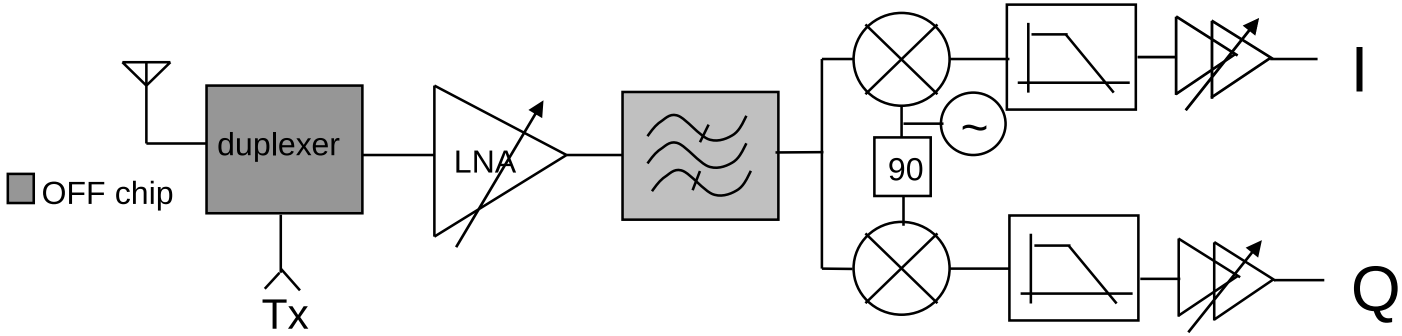
Summary of architected WCDMA receiver (in-band):



SNR calculator	**QPSK**	**Unit**	**SNR impact**
sensitivity Requirement (3.84MHz)	**-117 (+25)**	dBm	dB
Thermal Noise	-105.2	dBm	13.2
IIP3	-102.2	dBm	10.2
IIP2	-102.2	dBm	10.2
LO Phase Noise (IPE)	-114.2	dBm	22.2
receprocal mixing	-116	dBm	24
IM2 due to Tx leakage	-109.2	dBm	17.2
IM3 due to Tx leakage	-108.2	dBm	16.2
Image (I/Q mismatch)	-112.2	dBm	20.2
Analog Filter	-115	dBm	23
ADC Qn	-117.2	dBm	25.2
Total	-97.2	dBm	
Total SNR (target is 5.2dB)	**~5.2**	**dB**	

Though many impairments has >15dB SNR, but combined together, the entire system barely meets the 5.2dB SNR requirements.

Summary of architected WCDMA receiver (black-box specifications:



Rx NF: 3dB at the LNA input

Rx max gain: 103dB

Rx gain AGC: 82dB

I/Q demod IIP2: +29dBm

ADC DR: 6bits

Baseband filter ACR: 33dB

I/Q gain imbalance: 1.5dB

PLL f_{comp}: 200kHz

LNA gain step: 22dB

LNA IIP3 Tx offset: -3.9dBm

baseband AGC: 60dB

I/Q demod 10/20MHz IIP3: -3.9dBm

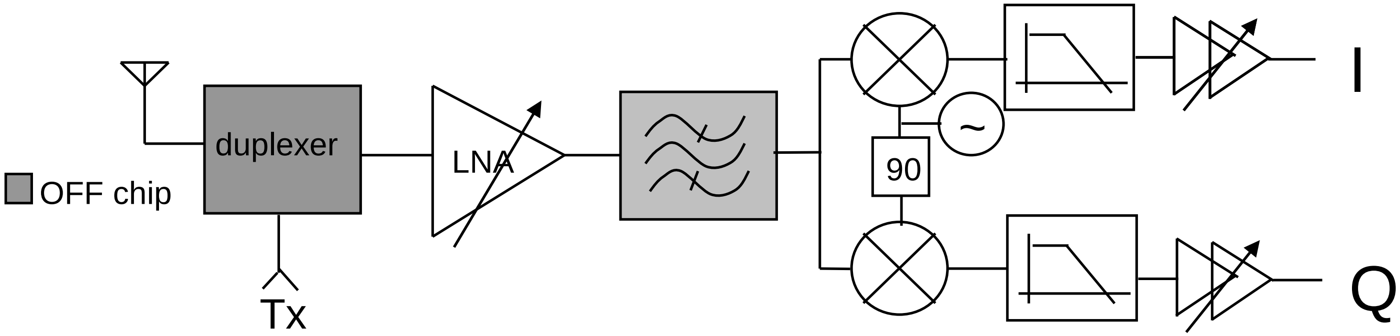
LO phase noise: -136dBc/Hz @ 10MHz

EVM: 20% max

I/Q phase imbalance: 4°

PLL integrated phase error: 4.5°

How to spec individual-blocks in the receiver?



Once receiver black-box specifications are known. For each one of these specs (say IIP3), you assign an individual specification (IIP3) for all blocks in the receiver; LNA, mixer, filter, VGA, etc so that the cascaded IIP3 meets the overall receiver black-box IIP3 spec. The assigned IIP3 spec for each of these blocks depends on how difficult/feasible to implement and the cost of implementation in terms of supply current, die area and risk. This is a highly iterative process between system engineer and design engineer to reach a consensus.

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[1] B. Razavi, “Design Considerations for Direct-Conversion Receivers,” *IEEE Tran. on Circuits and Systems – II,* Vol. 44, pp. 428 – 435, June 1997

[2] O. K. Jensen, *et al.*, “RF receiver requirements for 3G W-CDMA mobile equipment,” *Microwave Journal*, vol.43, Feb. 2000, pp.22–46.

[3] Aaron Netsell, “Interpret and Apply EVM to RF system design,” Microwave & RF, December 2001 issue, pp. 83-94

[4] D. Pimingsdorfer et. Al., “Impact of SAW RF and IF filter characteristics on UMTS transceiver system performance,” Ultrasonics 1999 Symposium Proceedings, Vol. 1, pp. 365-368.

[5] W. Ali-Ahmad, “Effective IM2 Estimation for Two-Tone and WCDMA Modulated Blockers in Zero-IF Receiver,” *RF Design*, April 2004, pp. 32-40.