RECEIVER ARCHITECTURES

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Topics

1. Main analog components for receivers
   - *amplifiers*
   - *filters*
   - *mixers*
   - *oscillators*

2. Receiver architectures and their properties
   - *superheterodyne principle*
   - *direct conversion*
     - *DC offsets as a challenging problem*
   - *low IF, Weaver*
   - *effects of I/Q imbalance*

3. Non-idealities and performance measures of the analog front-end components
   - *sensitivity, dynamic range*
   - *noise figure*
   - *intermodulation distortion, IP3*
   - *leakage, spurious frequencies*
   - *phase noise*

What is needed in the receiver front-end?

- Amplification to compensate for transmission losses
- Selectivity to separate the desired signal from others
- Tunability to select the desired signal

In the following we examine different receiver architectures and non-idealities affecting in the different building blocks used in the receivers.

Main Analog Components for Receivers

- ***Amplifiers***

  - Low-noise amplifiers (LNAs) in the first stages.

  - Automatic gain control (AGC) needed to cope with different signal levels.

- ***Filters***

  - Impossible to achieve sufficient selectivity by tunable RF filters (operating in the RF frequency band of the modulated signal) to separate the desired signal from others.

  - Sufficient selectivity can be achieved by fixed (IF) filters based on special technologies (SAW, Surface Acoustic Wave, ceramic, crystal, mechanical) in the hundreds of kHz to hundreds of MHz range.

    or analog filters operating on basedband or low bandpass center frequencies (up to MHz range)

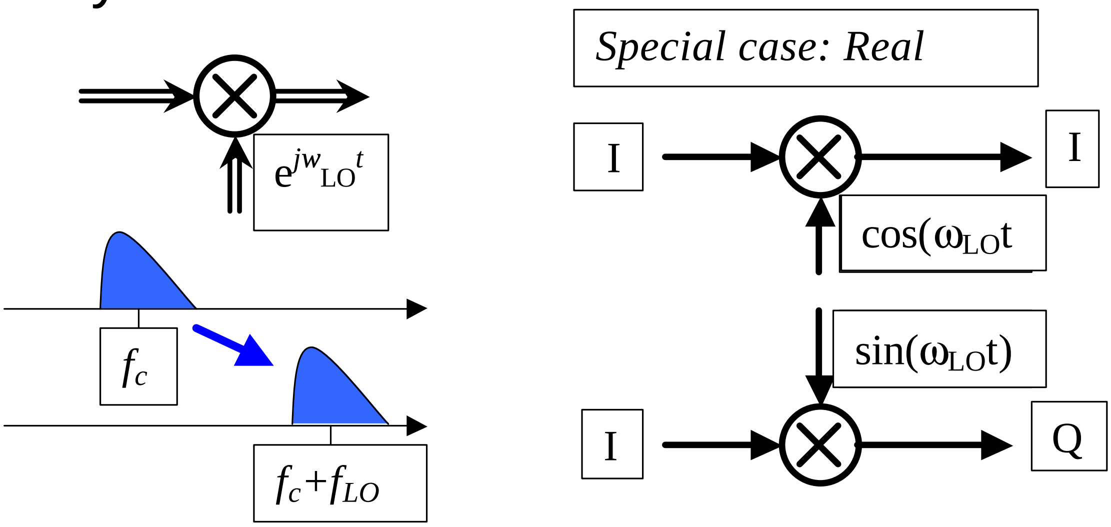
    (*or* multirate digital filters up to tens of MHz range).

  - Special complex filters, *phase splitters* (related also to Hilbert transformers) can be used to suppress certain frequency range from the negative part of the frequency axis. Such filters find application in certain special receiver architectures.

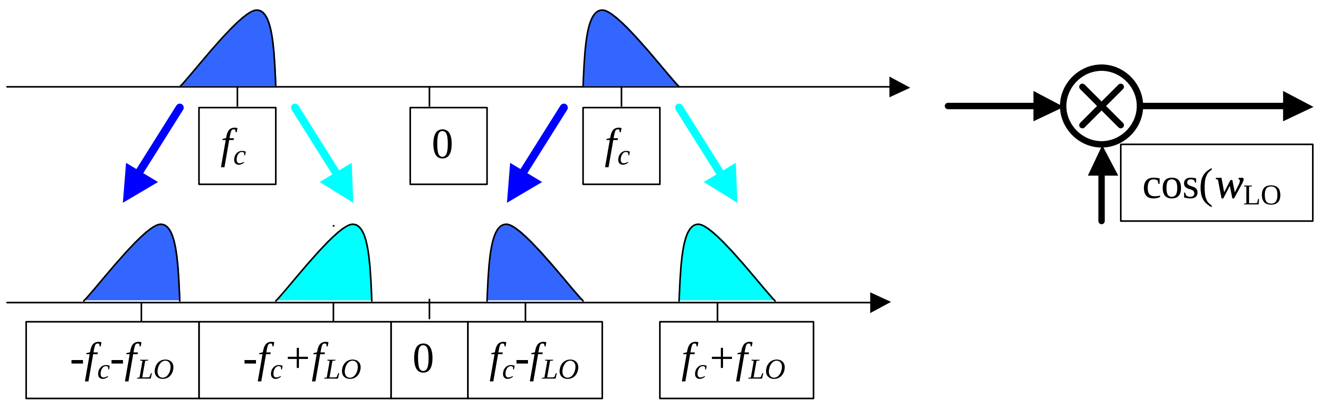
Main Analog Components for Receivers

- ***Mixers***

  - Complex (I/Q, quadrature) mixer: pure frequency translation by the local oscillator frequency:



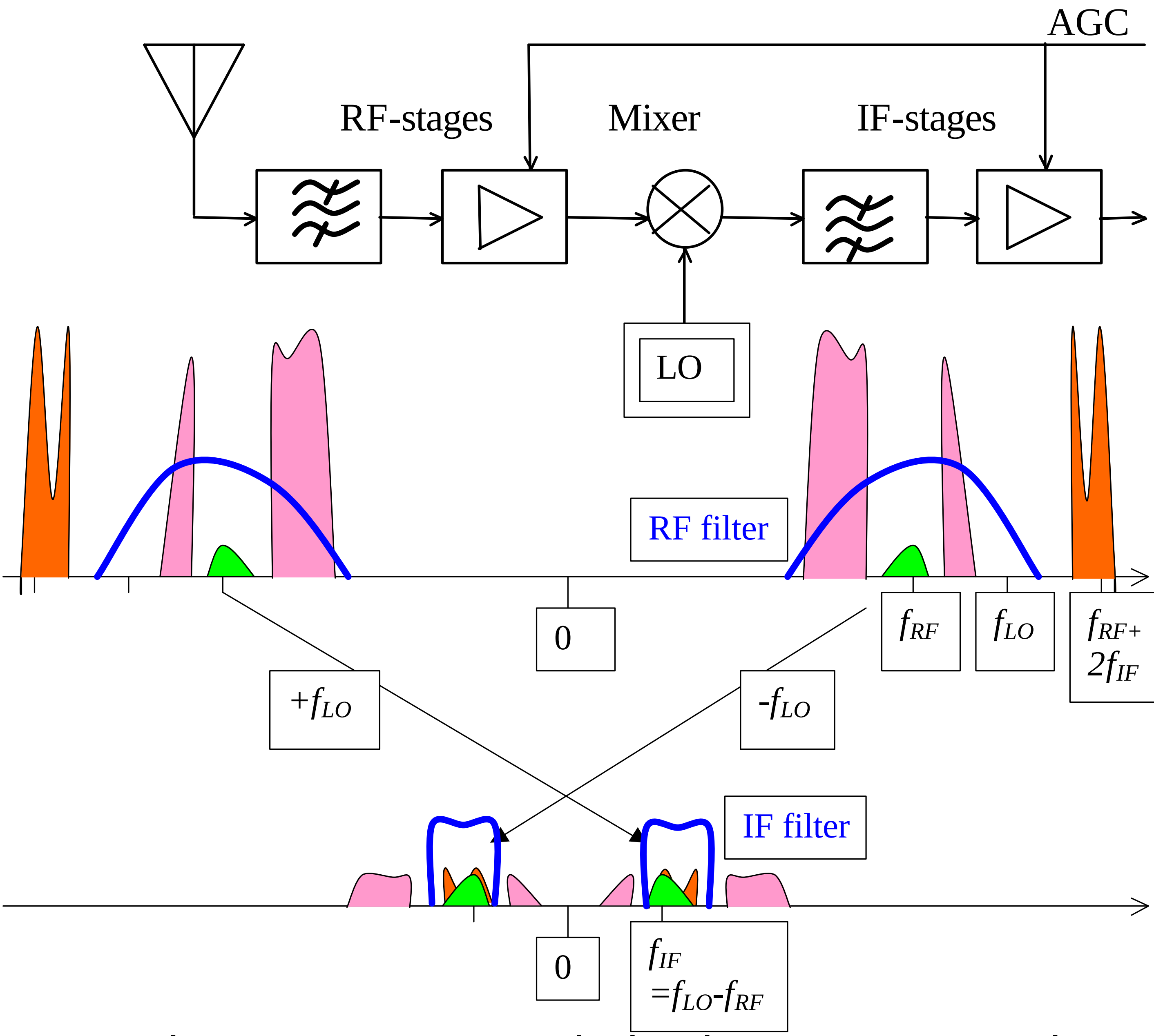
  - Real mixer produces the combination of frequency translations in both directions:



- ***Oscillators***

  - Voltage (or current) controlled oscillators (VCO, ICO) to achieve the tunability.

Classical Receiver Architecture: The Superheterodyne



Example: One common choice in GSM900 receivers is: 1st IF = 71 MHz, 2nd IF = 13 MHz

Vast majority of all the receivers are based on the superheterodyne principle.

Filtering Requirements in Superheterodynes

Selectivity is achieved at the IF stage(s) working at fixed center frequency using special filter technologies.

- The RF filter should provide sufficient attenuation for the image band at the distance of 2xf_{IF} in frequency.
- The final IF stage should have sufficient selectivity to suppress the neighbouring channels sufficiently.
- In case of double (or triple) super heterodyne, the first (and second) IF stage shoud provide enough attenuation at twice the next IF frequency.
- Image reject mixer is one possibility to reduce the RF filter requirements (but not sufficient as the only solution)

Alternatives in Superheterodynes

Down-conversion rx

- $f_{IF} << f_{RF}$
- easier to get good selectivity at first *IF*

Upconversion rx

- $f_{IF} > f_{RF}$
- easier to get good image rejection

Low-side LO injection

- $f_{LO} < f_{RF}$
- image band below f_{RF}

High-side LO injection

- $f_{LO} > f_{RF}$
- image band above f_{RF}
- spectrum inverted

Drawbacks of the Superheterodyne Architecture

Some parts are difficult to integrate

- IF-filter
- RF-filter
- Oscillators

Power consumption high

- external components => parasitics
- several submodules => low impedance (e.g., 50 Ω) levels used for matching the modules

Complicated structure.

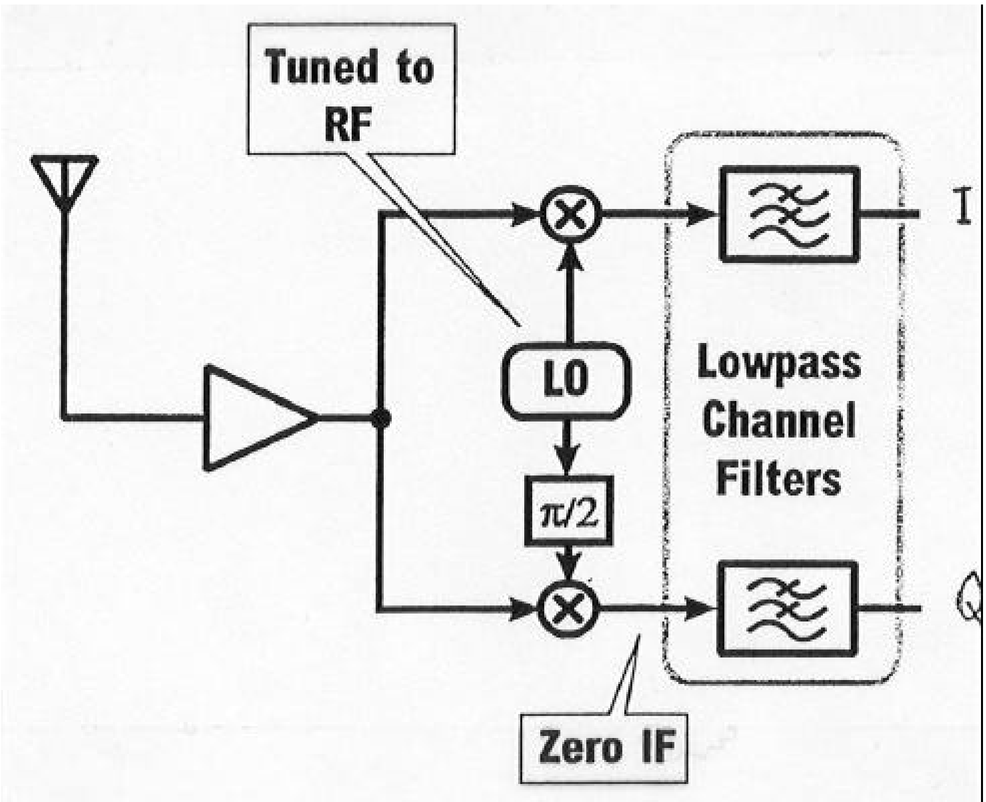
➔ There is interest for simpler architectures which could be integrated more easily.

Spurious responses

LO and IF signals and harmonics and mixtures leaking to different places may cause problems.

Direct Conversion Receiver Architecture

"Zero IF"



Advantages

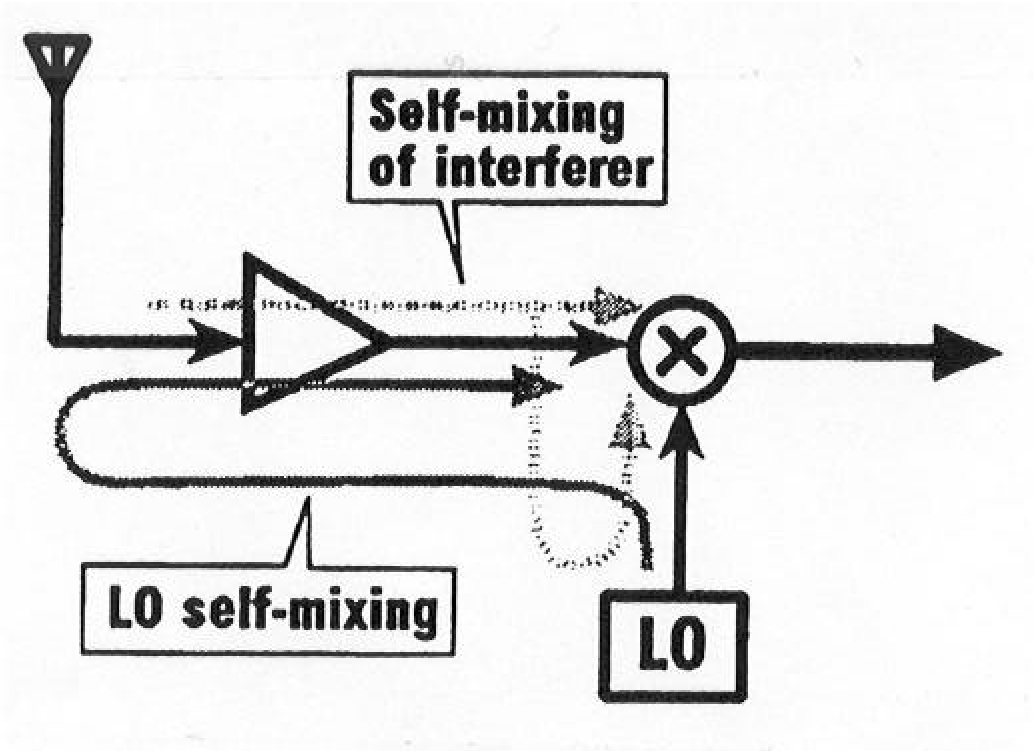
- No image bands
  => RF-filtering not so critical
- Simple structure, no IF filters
- Not so much spurious responses

Problem: Difficult to implement (dc offsets, leakage between rx and tx in full duplex operation)

Examples: Alcatel DECT and GSM receivers
Nokia 1611 GSM phone

DC-Offsets in Direct Conversion Receivers

DC-offsets appear mainly due to LO leakage:



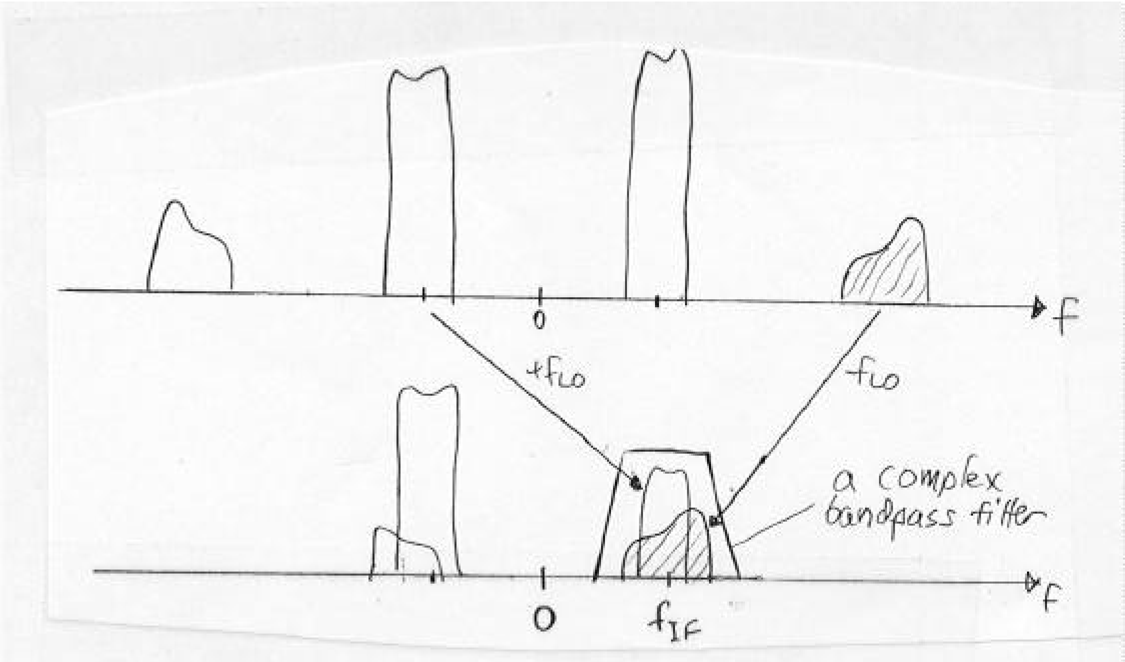
Constant DC-offset can be compensated by measuring it without signal and then subtracting it during reception.

In TDMA systems, different channels/bursts may have different signal levels and different AGC-values and hence different DC-offsets => compensation is difficult.

Also 1/f -type of noise appearing in active components may be a problem.

Low IF Receiver Architecture

The idea is to use quadrature down-conversion and a low IF frequency which is just high enough to cope with the DC-offset problem (e.g., 250 kHz in case of GSM).



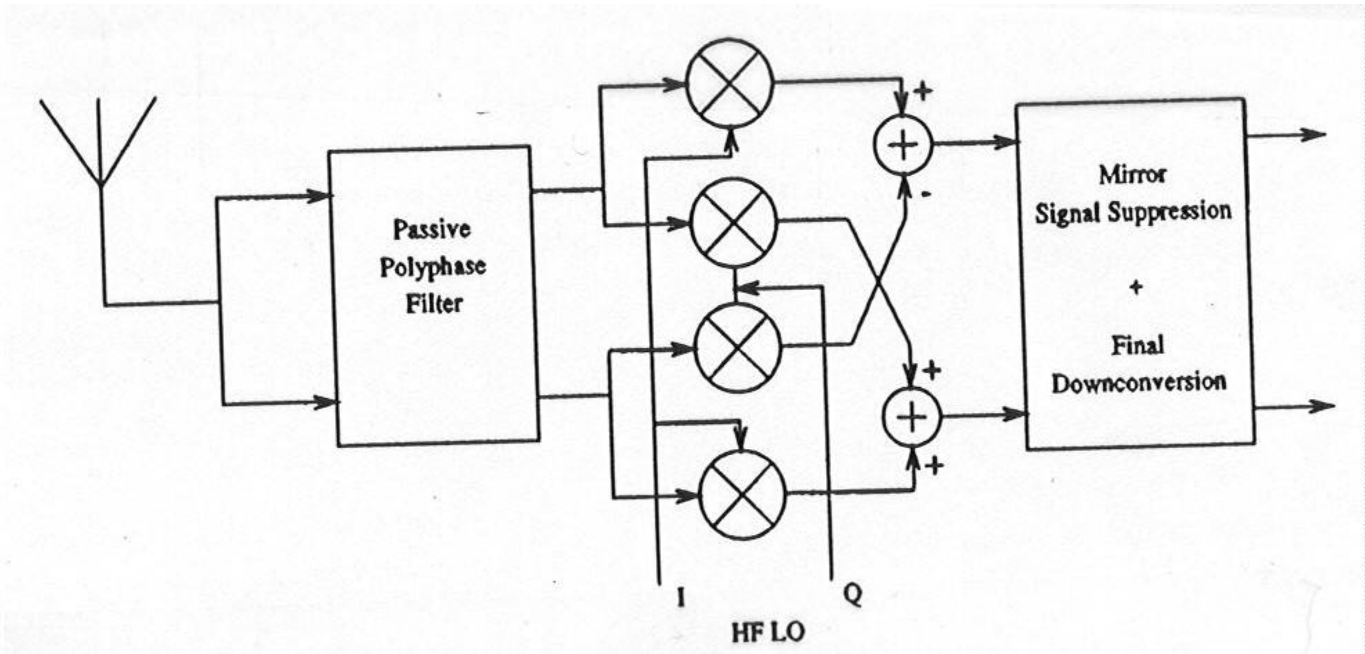
As we shall see on the next pages, quadrature downconversion cannot, in practice, provide sufficient attenuation for the image band.

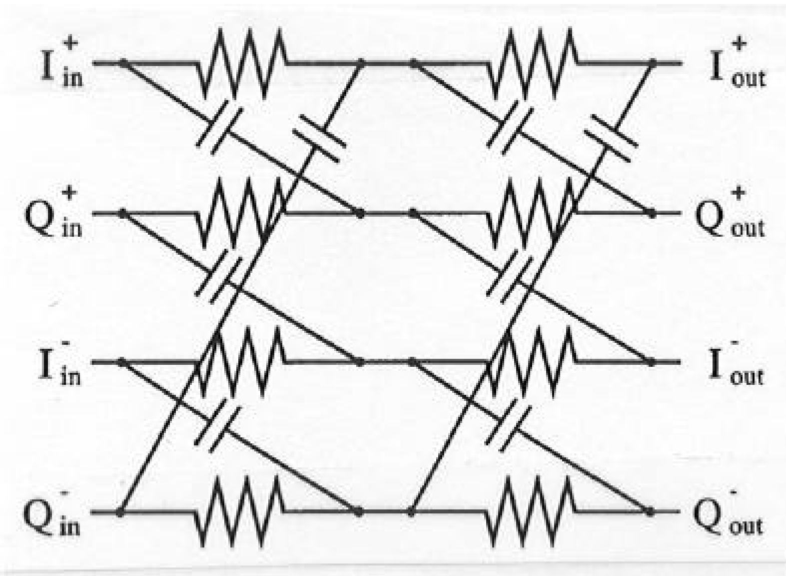
More attenuation can be obtained by using a phase splitter attenuating the image band on the negative part of the frequency axis.

Even more attenuation could possibly be achieved through baseband digital signal processing.

The low-IF concept is facilitaed by the fact that system specifications (like GSM) don't allow the maximum signal level to appear in the nearest adjacent channels in case of a very low desired signal level.

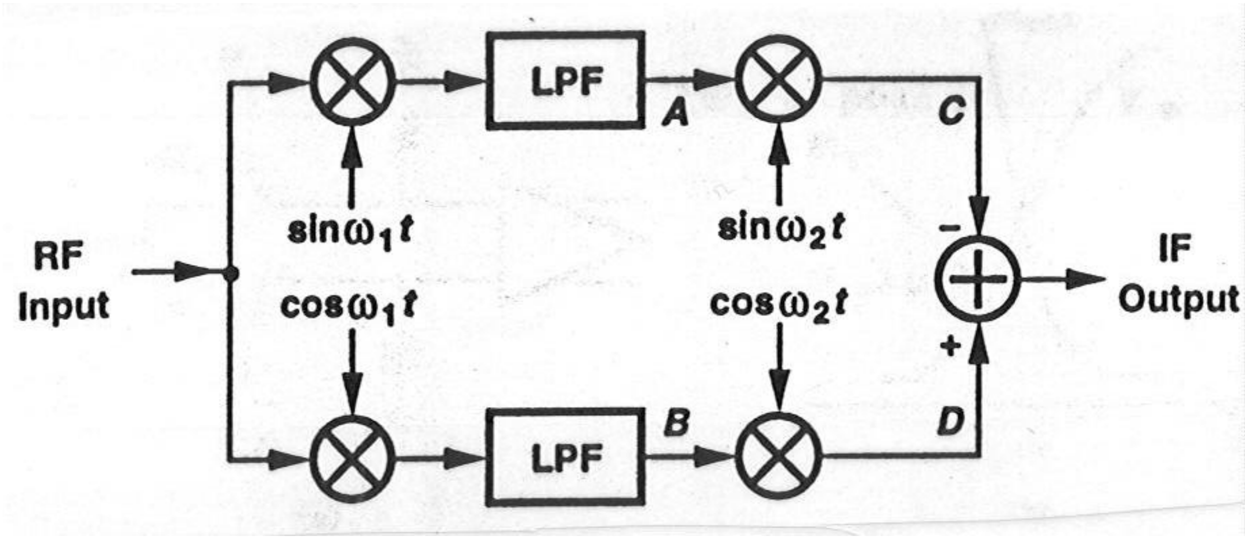
Low IF Receiver by Steyert *et al.*





In this architecture, the image is suppressed 25 … 30 dB by the phase splitter implemented as a polyphase RC network, and another 25 … 30 dB by the quadrature downconversion approach.

Weaver
Receiver Architecture



Here the first LO frequency is fixed (using e.g., an IF frequency of about 200 MHz in a DECT example) and the second LO is used for channel selection.

In this architecture, the requirements for RF and IF filtering are mild, and the channel selectivity is implemented at baseband.

DC-offset problems of direct conversion receiver can be reduced because there can be more amplification before the second mixer.

Oscillator Phase Quadrature, Gain and Phase Imbalance in I/Q Systems

Quadrature downconversion is trying to produce a pure frequency translation which would suppress the image band completely.

In practice, there is some missmatch (imbalance) of gain and/or phase in the components involved (oscillator, amplifiers, mixers).

Consequently, the image suppression is, in practice, far from complete.

Image Rejection as a Function of Gain and Phase Imbalance

Assuming that g is the gain imbalance ration and f is the phase difference due to imbalance, we can write:

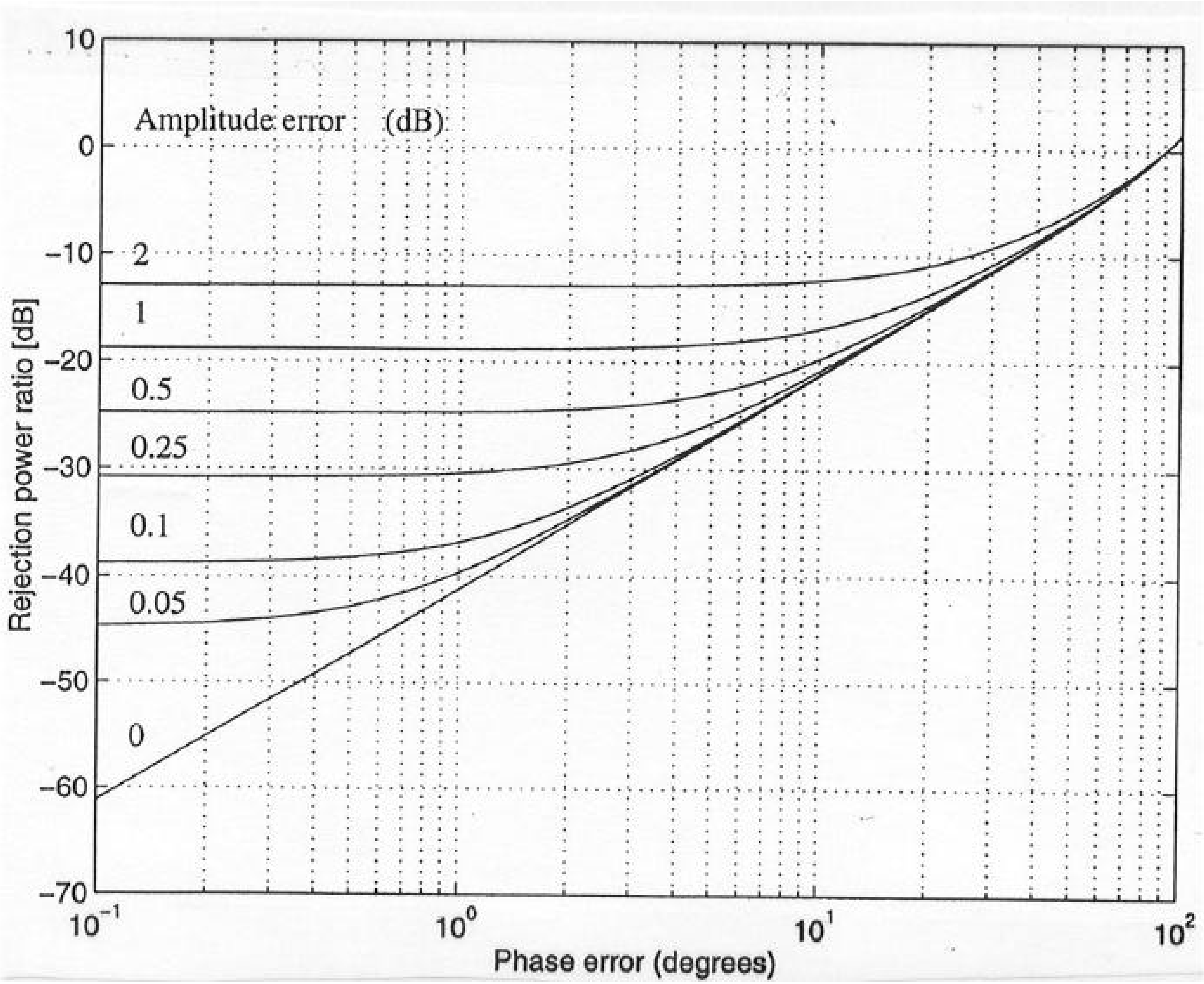
$$
\begin{aligned}
y(t) &= x(t)\left[\cos w_c t + jg\sin(w_c t + f)\right] \\
&= x(t)\left[\frac{e^{jw_c t} + e^{-jw_c t}}{2} + g\,\frac{e^{j(w_c t + f)} - e^{-(jw_c t + f)}}{2}\right] \\
&= x(t)\left[e^{jw_c t}\,\frac{1 + ge^{jf}}{2} + e^{-jw_c t}\,\frac{1 - ge^{-jf}}{2}\right]
\end{aligned}
$$

From the latter form, we can identify the strength of the two spectral components produced by the two frequency translations, and the (power) rejection of the image is obtained as

$$
R^2 = \frac{\left|\dfrac{1 - ge^{-jf}}{2}\right|}{\left|\dfrac{1 + ge^{jf}}{2}\right|} = \frac{1 + g^2 - 2g\cos f}{1 + g^2 + 2g\cos f}
$$

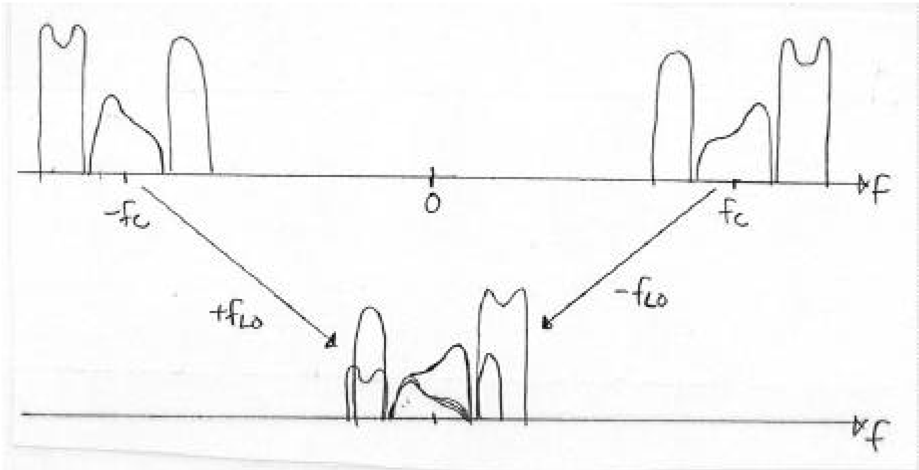
This result can be applied to all cases of quadrature mixing where gain and/or phase imbalance appears.

Image Rejection as a Function of Gain and Phase Imbalance



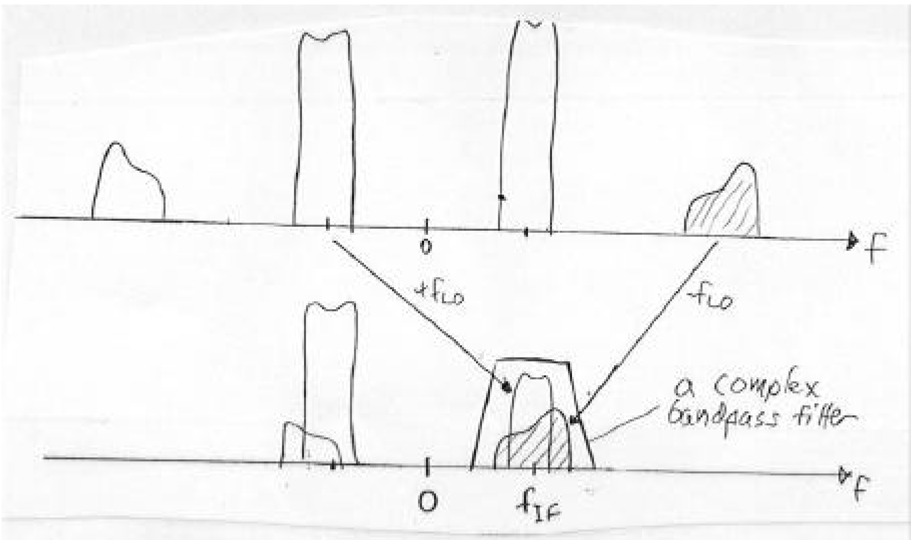
Effects of Gain and Phase Imbalance

In case of direct conversion receiver (or final demodulation of an I/Q-signal), gain mismatch and phase errors cause "self images":



This usually not a problem, or if it is, it can be compensated in baseband processing. In the baseband signal, self imaging appears as a distortion (linear transformation) of the constellation, which usually can be inverted.

In other cases of quadrature down-conversion, the image signal may be at a considerably strongerer (up to 100 dB!!) level than the desired signal, and I/Q imbalance is very critical:



Summary:
Techniques for Providing Image Rejection in Different Architectures

In direct conversion architectures images are not a problem.

In other architectures (superheterodyne, low IF, Weaver) images are a problem, and the following techniques can be used:

1. RF, first IF filters
   - Challenges to get sufficient performace in integrated solutions.
   - Not applicable in low IF.
2. Quadrature down-conversion
   - Rejection limited by gain and phase imbalance.
   - Utilized in some cases also in superheterodynes ("image reject mixer") to simplify the RF filter.
   - Produces complex signal and the consequtive signal processing blocks must be duplicated.
3. Phase splitter (passive polyphase RC network)
   - Produces complex signal and the consequtive signal processing blocks must be duplicated.
4. Baseband digital signal processing

Selectivity Tradeoffs

Selectivity at IF *(superhet)*
- high-cost IF filters
- less demands for analog circuits after IF
- simple A/D converter

Selectivity by analog baseband processing
(direct conversion or low-IF case)
- no costly IF filters
- more RF gain needed
  => RF has to very linear to avoid intermodulation effects
- simple A/D converter

Selectivity by baseband digital filtering
- no costly IF filters
- high dynamic range A/D-converters (14…17 bits)
- more RF gain with high linearity needed

Selectivity by digital filtering after wideband IF sampling
- simplified IF filter
- high dynamic range A/D-converters (14…17 bits)
- very strict demands for low jitter sampling clock

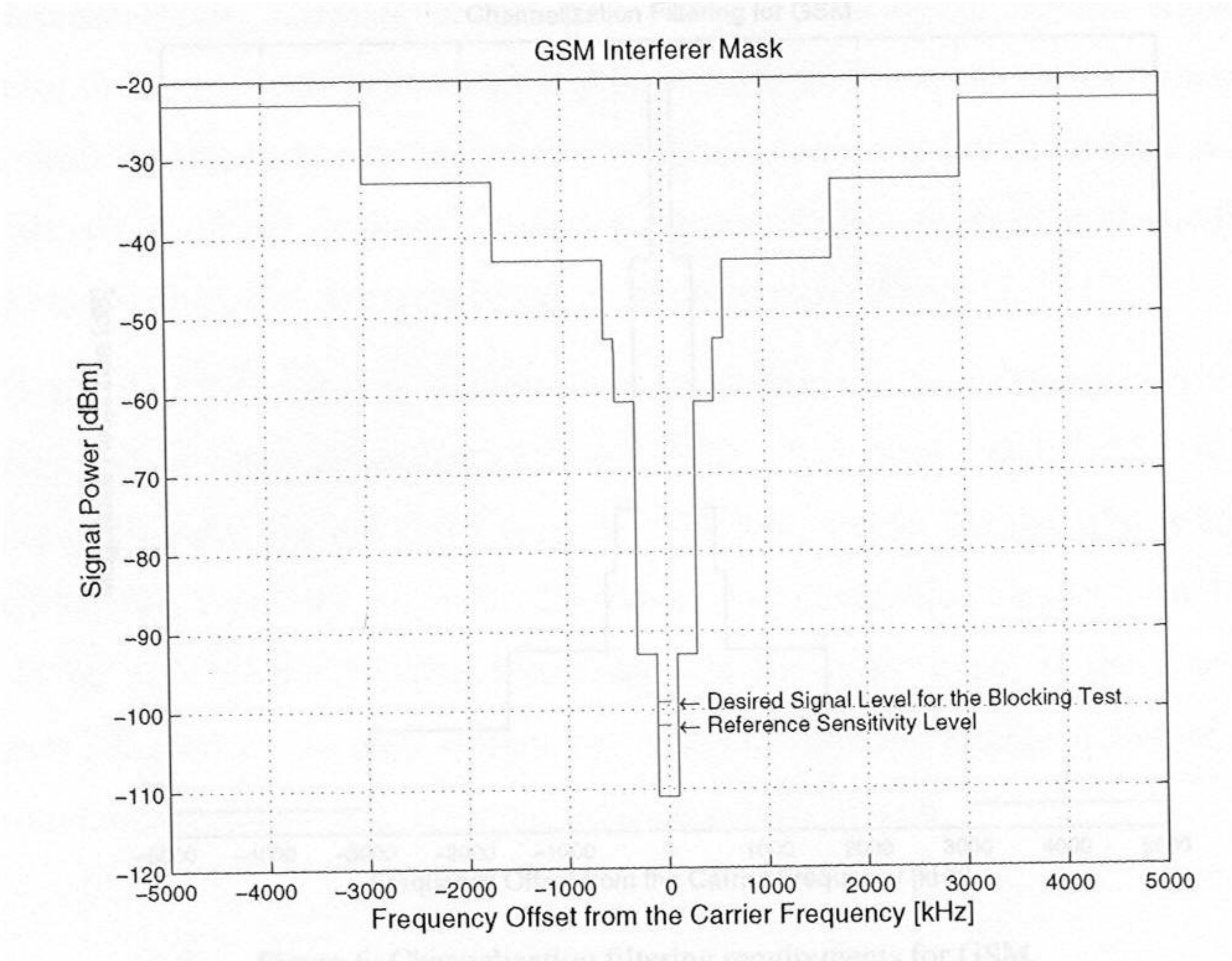
Selectivity Requirements in System Specifications

Radio system specifications (e.g., for cellular systems) don't allow a strong adjacent channel signal to be present when a weak desired signal is to be received. (Radio Resource Mangement takes care of this!)

For example, the GSM specifications give:

- The maximum level for the 3 *adjacent channels* on both sides (at 200, 400 and 600 kHz from the carrier) in case of a GSM interferer and desired signal 20 dB above the reference sensitivity level of -102 dBm.
- Maximum levels for more distant signals (>600 kHz from carrier), *blocking signals*, in case of a sinusoidal interferer and desired signal 3 dB above the reference sensitivity level.

GSM Interference Mask



Non-Idealities and Performance Measures of the Analog Front-End Components

- ***Sensitivity*** of the receiver is mainly determined by the noise produced by the receiver front-end components. It determines the minimum detectable signal in noise-limited situation. In general:

  Receiver sensitivity = *thermal noise power* (dBm)
  + *noise figure* (dB)
  + *required SNR* (dB)
  + *implementation loss* (dB)

  In room temperature:

  Thermal noise power (dBm) $= -174\ \text{dBm} + 10\log_{10} B$

  where B is the equivalent noise bandwidth of the rx.

  For example in GSM, min. S/N is 9 dB, B=200 kHz, and required sensitivity is -102 dBm => NF<10 dB.

- With low received signal levels, the receiver front-end components can be assumed to be linear. With higher signal levels, the ***nonlinearity*** of the amplifiers and other components produce harmful ***intermodulation*** products. In this way the nonlinearity and intermodulation effects limit the ***dynamic range*** of received signals from above.

  Intermodulation is measured by 1 dB compression point or the so-called ***IP3*** figure.

  Balancing between sensitivity and intermodulation requirements is an important part of the receiver design.

Non-Idealities and Performance Measures of the Analog Front-End Components *(continued)*

- ***Frequency accuracy and stability*** are determined by the local oscillators of the receiver. In systems like GSM, the receiver is locked to the network, and the frequency stability is very good. However, to guarantee that the receiver is able to synchronize to the network, certain frequency accuracy, stability, and settling time requirements are set for the components.

  The short term instability of the oscillators appear as ***phase noise***, and it is very critical for the performance of the system.

- ***Leakage*** effect means that strong signals, especially local oscillator signals are connected, e.g., through spurious capacitances to places where they are not supposed to be connected. This means that various harmonics, subharmonics, and mixtures of the local oscillator frequences are usually connected to the signal.

  In receiver design, the frequencies of the strongest ***spurious frequencies*** can be calculated. By selecting the local oscillator frequencies properly, most of the spurious frequencies can be placed outside the desired frequency bands in RF and IF.

- In the case of analog I/Q signal processing, amplitude phase responses of the I and Q branches are never exactly the same. The ***effects of the gain and phase imbalance*** depend greatly on the receiver architecture.

Noise Figure

The noise factor of an amplifier stage (or some other component) is determined by the ratio of S/N (or C/N) ratios at the input and output:

$$F = \frac{CNR_{in}}{CNR_{out}}$$

and the noise figure is

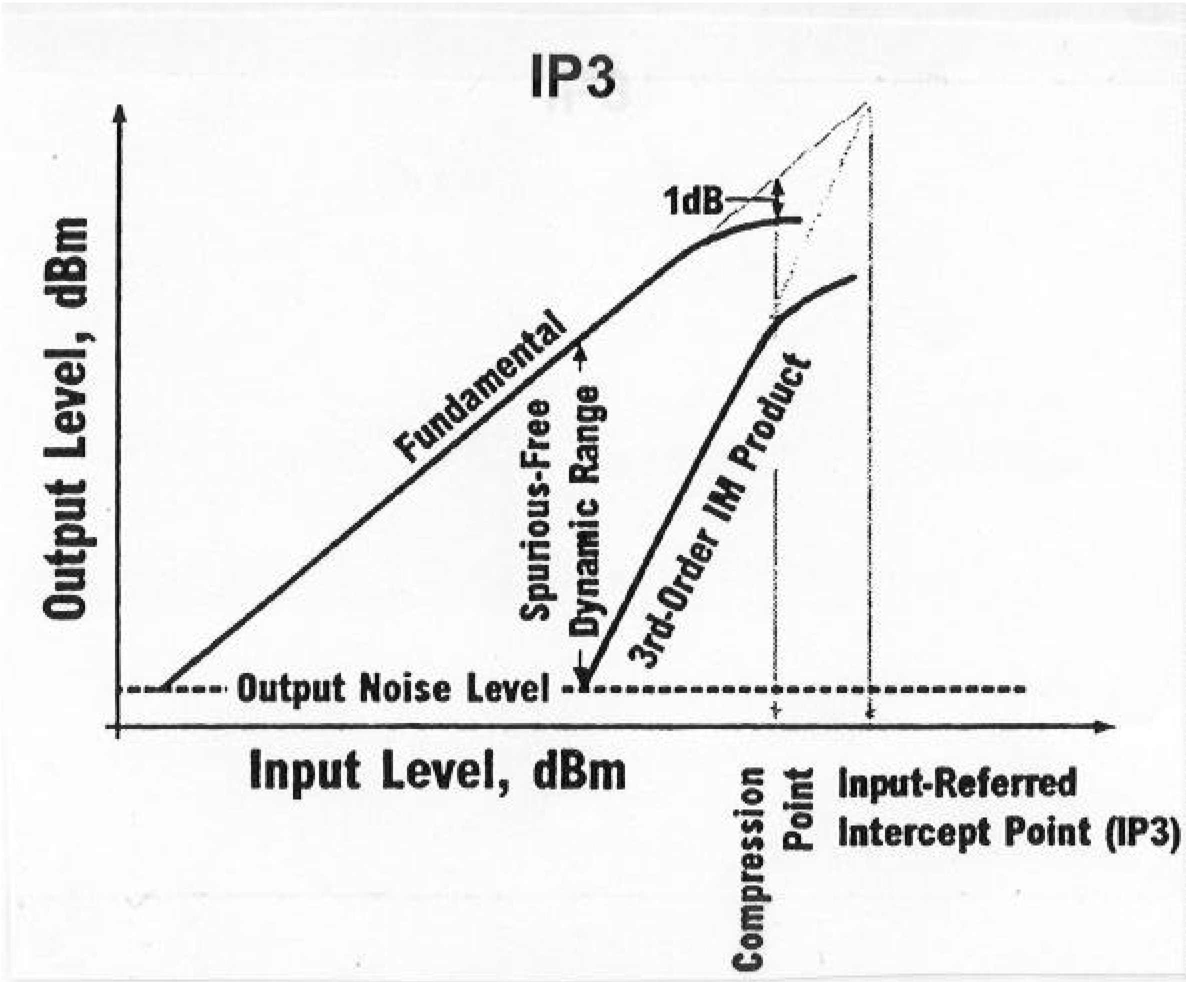
$$NF = 10 \log_{10} F \,.$$

For a cascade of amplifier stages, the overall noise figure is

$$F_T = F_1 + \frac{F_2 - 1}{g_1} + \frac{F_3 - 1}{g_1 g_2} + \Lambda + \frac{F_n - 1}{g_1 g_2 \Lambda \; g_{n-1}}$$

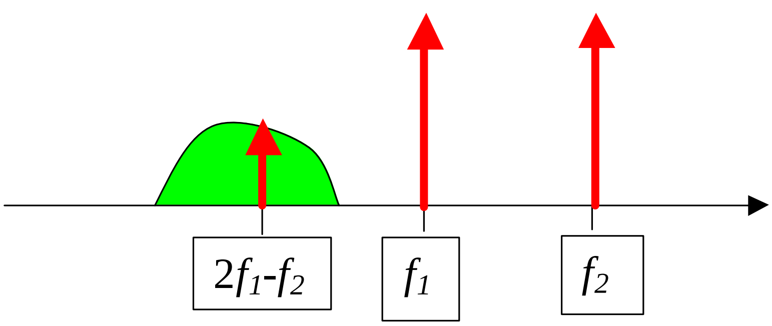
where F_i and g_i are the noise factor and power gain of section i.

A passive component at the front-end (e.g., duplexer or RF filter) usually has a good noise figures, but its attenuation enhances the effects of the following noisy amplifier stages.



IP3 determines the strength of third-order intermodulation products at the amplifier output.

Consider a test where there are two nearby frequencies f_1 and f_2 in the system frequency band (like in the neighbouring channel). Third-order intermodulation produces frequencies $2f_1 - f_2,\quad 2f_2 - f_1$ which may be in the signal band.



IP3 for a Cascade of Amplifiers

The overall *output*-referred IP3 can be estimated from the *output*-referred IP3-values and power gains of the stages. There are two alternative formulas:

$$IP3[W] = 1 / \sum_i \frac{1}{IP3_i \, g_{i+1} g_{i+2} \Lambda \; g_n}$$

$$IP3[W] = 1 / \sqrt{\sum_i \frac{1}{IP3_i \, g_{i+1} g_{i+2} \Lambda \; g_n}}$$

The first one assumes noncoherent summation of the distortion products, the latter one assumes coherent summation.

The first formula is said to give more realistic results, but the latter one is safer and it is widely used in dimensioning the system.

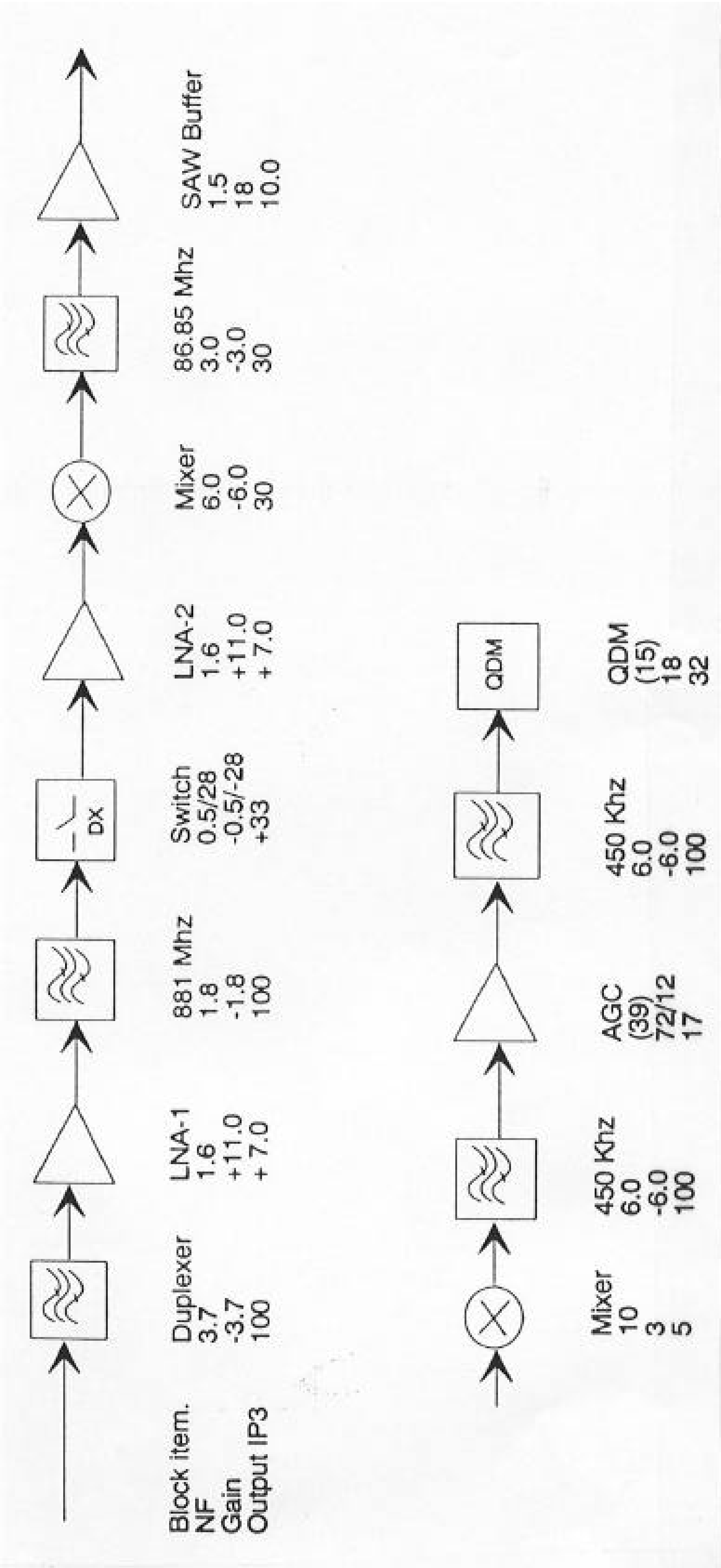
Effects of 2nd and 3rd-Order Intermodulation

2nd-order intermodulation products are clearly stronger than 3rd-order products.

=> If 2nd-order intermodulation products of some strong signals (blocking signals) appear on the signal band, then better linearity is required.

- In typical superheterodyne receivers, only 3rd-order intermodulation is a problem, because signals causing 2nd-order products on the signal band are attenuated by the RF filter.
- In wideband superhet with relatively low IF, also the 2nd-order intermodulation may become a problem.
- 2nd-order intermodulation is always a problem in direct-conversion and low-IF receivers.

Example: Analysing the Dynamic Range *(1)*



Example: Analysing the Dynamic Range *(2)*

Small-signal case: AGC is set so that the the amplifiers have maximum gain.

Table 2.7
Small-Signal Analysis Results from Figures 2.2 and 2.3

Receiver Blocks	*NF(dB)*	*Gain (dB)*	*Output IP3 (dBm)*	*Cascade NF (dB)*	*Cascade Gain (dB)*	*Cascaded IP3 (dBm)*	*Signal Strength (dBm)*
Input							−110.0
Duplexer	3.7	−3.7	100.0	3.7	−3.7	98.46	−113.7
LNA-1	1.6	11.0	7.0	5.3	7.3	7.0	−102.7
881-MHz filter	1.8	−1.8	100.0	5.42	5.5	5.2	−104.5
DX switch	0.5	−0.5	33.0	5.46	5.0	4.69	−105.0
LNA-2	1.6	11.0	7.0	5.63	16.0	6.45	−94.0
UHF mixer	7.0	−6.0	30.0	5.75	10.0	0.44	−100.0
86-MHz filter	3.0	−3.0	30.0	5.87	7.0	−2.56	−103.0
SAW buffer	1.5	15	10.0	5.96	22.0		
VHF mixer	10.0	23.0	5.0	6.02	45.0		
450-kHz filter	6.0	−6.0	100	6.02	39.0	Narrowband Signal	
AGC amp.	(39)	68.0	17.0	6.99	111.0		
450-kHz filter	6.0	−6.0	100.0	6.99	105.0		
QDM	(20)	18.0	32.0	6.99	123.0		

Table 2.8
Summary of Small-Signal Results from Figures 2.2 and 2.3

Performance Parameter	*Result*
KTB (BW = 24.3 kHz)	−130.14 dBm
NF	6.99 dB
System noise floor	123.15 dBm
Minimum signal E_s/N_0 (For 4-phase differential detection @ BER = 10^{-3})	12 dB
Implementation loss	1 dB
Required CNR in AWGN	13 dB
Sensitivity @ BER = 1e − 3	−110.15 dBm
Intended minimum signal	−110 dBm
Input IP3	−9.56 dBm
EISA IM method	
IS-55 -2.3.2.3	> 60 dB
IP3 /signal strength	> 20 dB minimum.

Example: Analysing the Dynamic Range *(3)*

Large-signal case: AGC is set so that the the amplifiers have minimum gain.

Table 2.9
Large-Signal Analysis Results from Figures 2.2 and 2.3

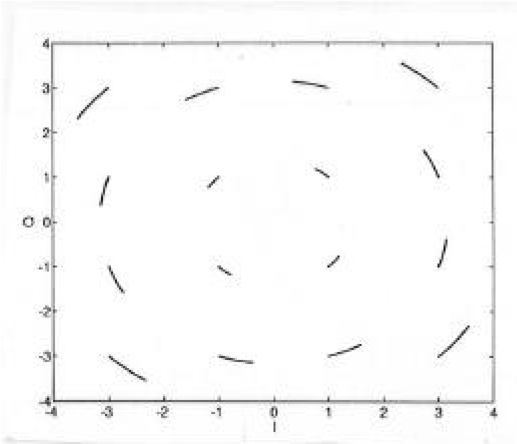
Receiver Blocks	*NF(dB)*	*Gain (dB)*	*Output IP3 (dBm)*	*Cascade NF (dB)*	*Cascade Gain (dB)*	*Cascaded IP3 (dBm)*	*Signal Strength (dBm)*
Input							−25
Duplexer	3.7	−3.7	100.0	3.7	−3.7	98.46	−28.7
LNA-1	1.6	11.0	7.0	5.3	7.3	7.0	−20.7
860-MHz filter	1.8	−1.8	100.0	5.42	5.5	5.2	−22.5
DX switch	28	−28	33.0	22.58	−22.5	−22.8	−50.5
LNA-2	1.6	11.0	7.0	24.15	−11.5	−1186	−39.5
UHF mixer	7.0	−6.0	30.0	25.01	−17.5	−17.86	−45.5
86-MHz filter	3.0	−3.0	30.0	25.72	−20.5	−20.86	−48.5
SAW buffer	1.5	15	10.0	26.22	−5.5		
VHF Mixer	10.0	3.0	5.0	26.54	−2.5		
450-kHz filter	6.0	−6.0	100	26.59	−8.5	Narrowband Signal	
AGC amp.	(39)	12.0	17.0	47.53	3.5		
450-kHz filter	6.0	−6.0	100.0	47.53	−2.5		
QDM	(20)	18.0	32.0	47.55			

Table 2.10
Summary of Large-Signal Results from Figures 2.2 and 2.3

Performance Parameter	*Results*
KTB (BW = 24.3 kHz)	−130.14 dBm
NF	47.55 dB
System noise floor	−82.59 dBm
Required signal CNR in AWGN	13 dB
Sensitivity @ BER=1*e* − 3	−69.59 dBm
Intended maximum signal	−25 dBm
IP3/signal strength	> 20 dB minimum

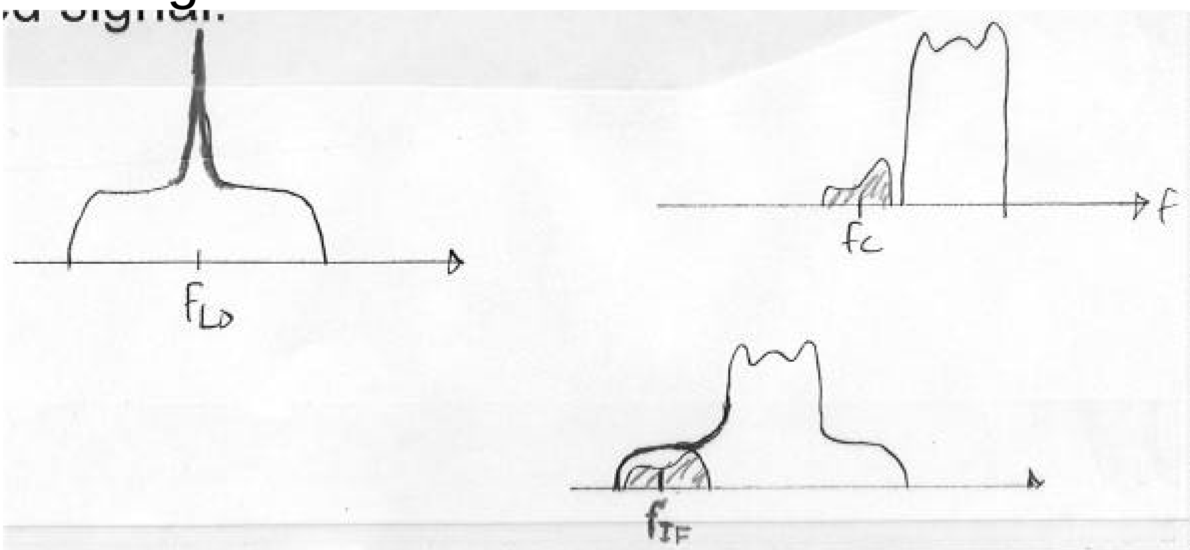
Non-Idealities in Oscillators

- Constant phase error rotates the constellation; Can be corrected by baseband processing afterwards
- Random phase errors reduce the noise margin in detection and increase BER:



- *Phase noise:* random fluctuations in the instantanous phase/frequency of the oscillator.

  Mixing products of the phase noise spectrum and strong adjacent channel signals (reciprocal mixing) may produce spurious signals which overlap the desired signal:



Example of Phase Noise Calculations

VCO phase noise in a GSM 900 handportable

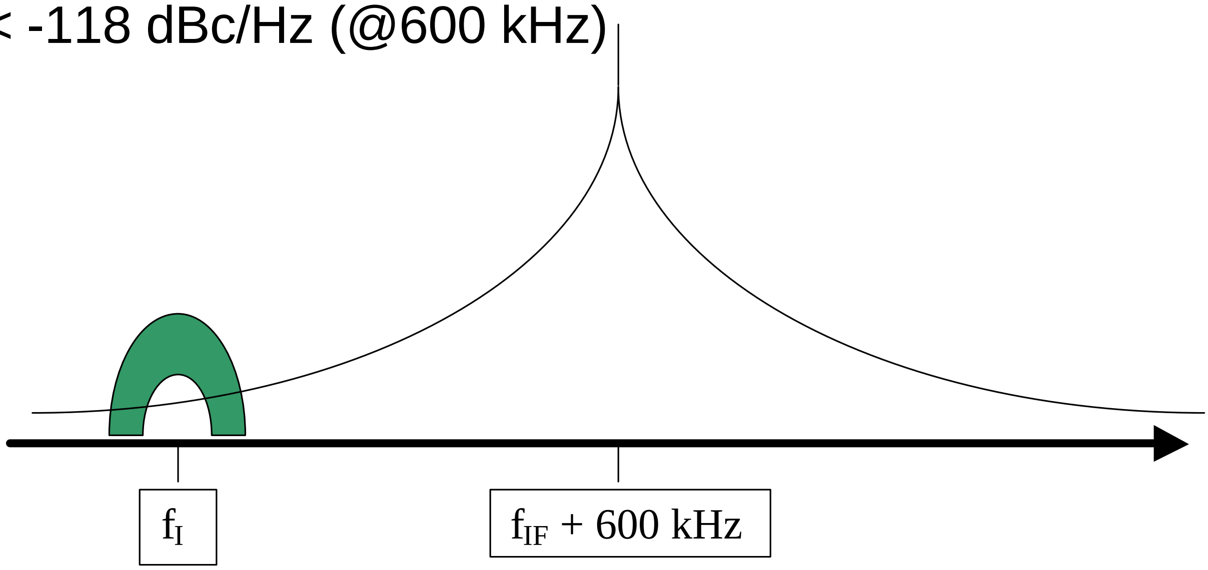
- wanted signal -102 dBm + 3 dB = -99 dBm
- blocking signal -43 dBm @ 600 kHz
- Minimum S/N=9 dB
- Noise bandwidth 200 kHz

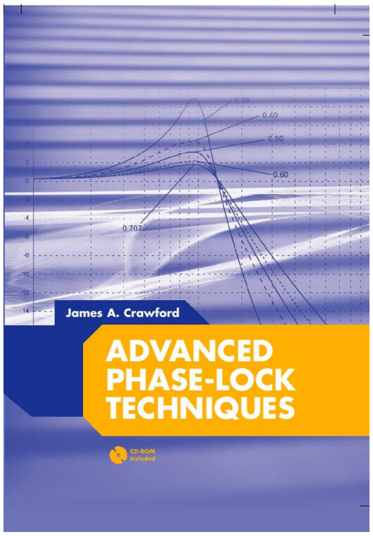
Assume that the phase noise spectrum is flat within the noise bandwidth with x dBc/Hz (i.e., the noise power in 1 Hz bandwidth is x dB in reference to the power of the VCO at the LO frequency)

=> noise power at noise bandwidth:

$$-43 \text{ dBm} + x + 10 \log_{10} 200000 < -99 - 9 \text{ dBm}$$

=> x < -118 dBc/Hz (@600 kHz)





Advanced Phase-Lock Techniques

James A. Crawford

2008

Artech House

510 pages, 480 figures, 1200 equations
CD-ROM with all MATLAB scripts

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