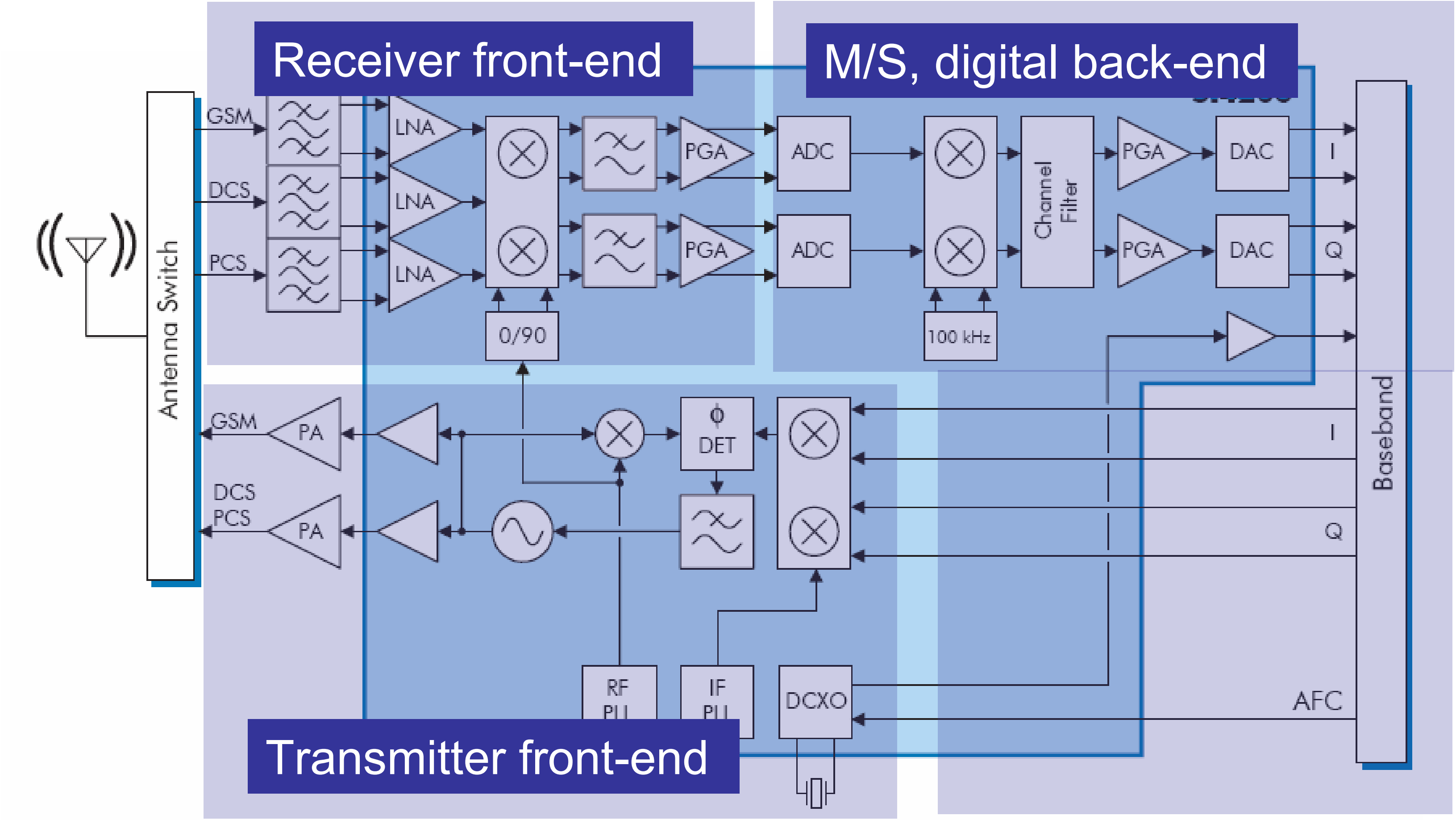
Receiver architectures

Introduction

Example of a complete transceiver



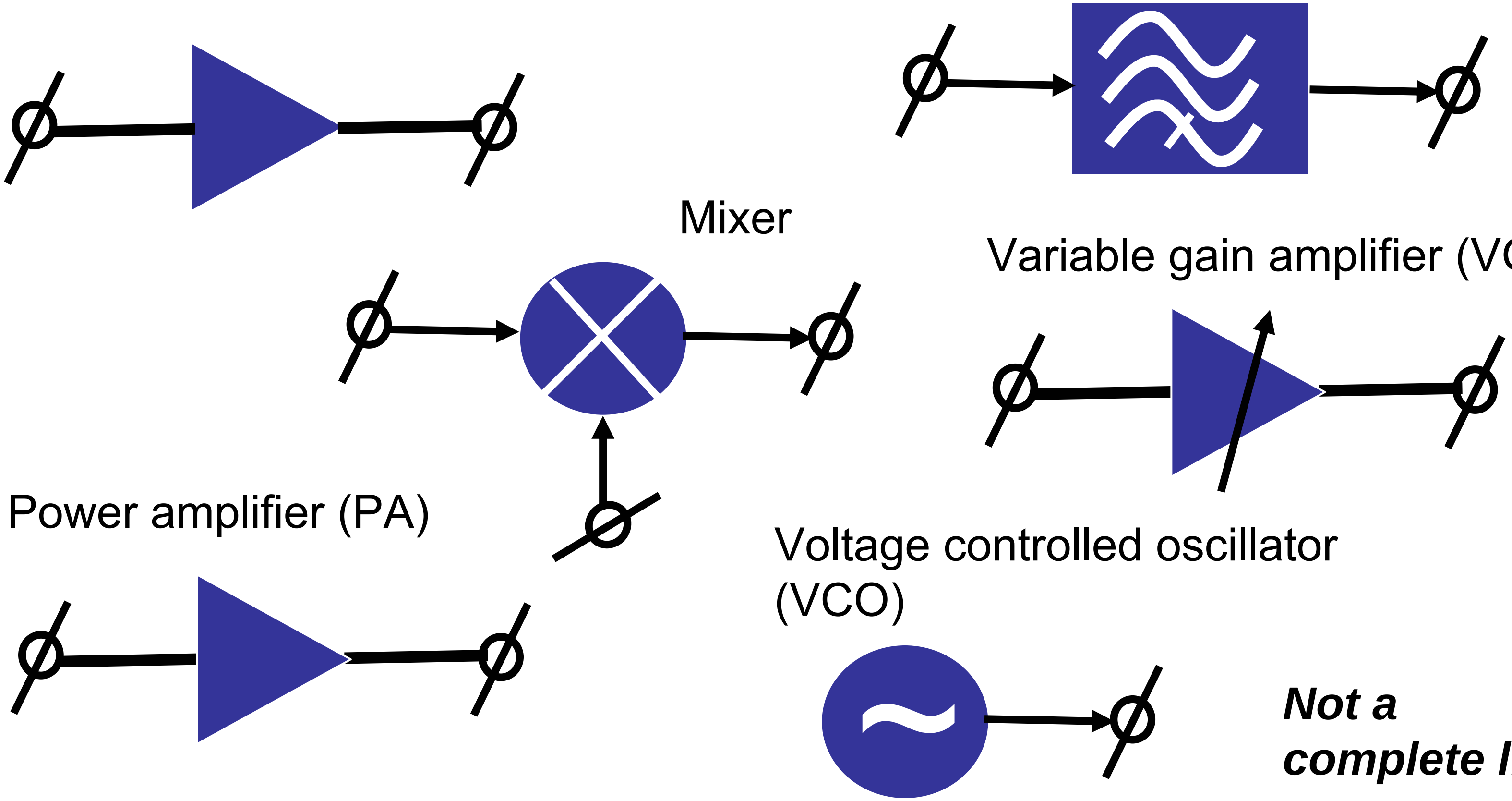
Receiver front-end

M/S, digital back-end

Transmitter front-end

Source: Silicon labs

RX (Receiver) / TX (transmitter) building blocks



Low Noise Amplifier (LNA)

Filter

Mixer

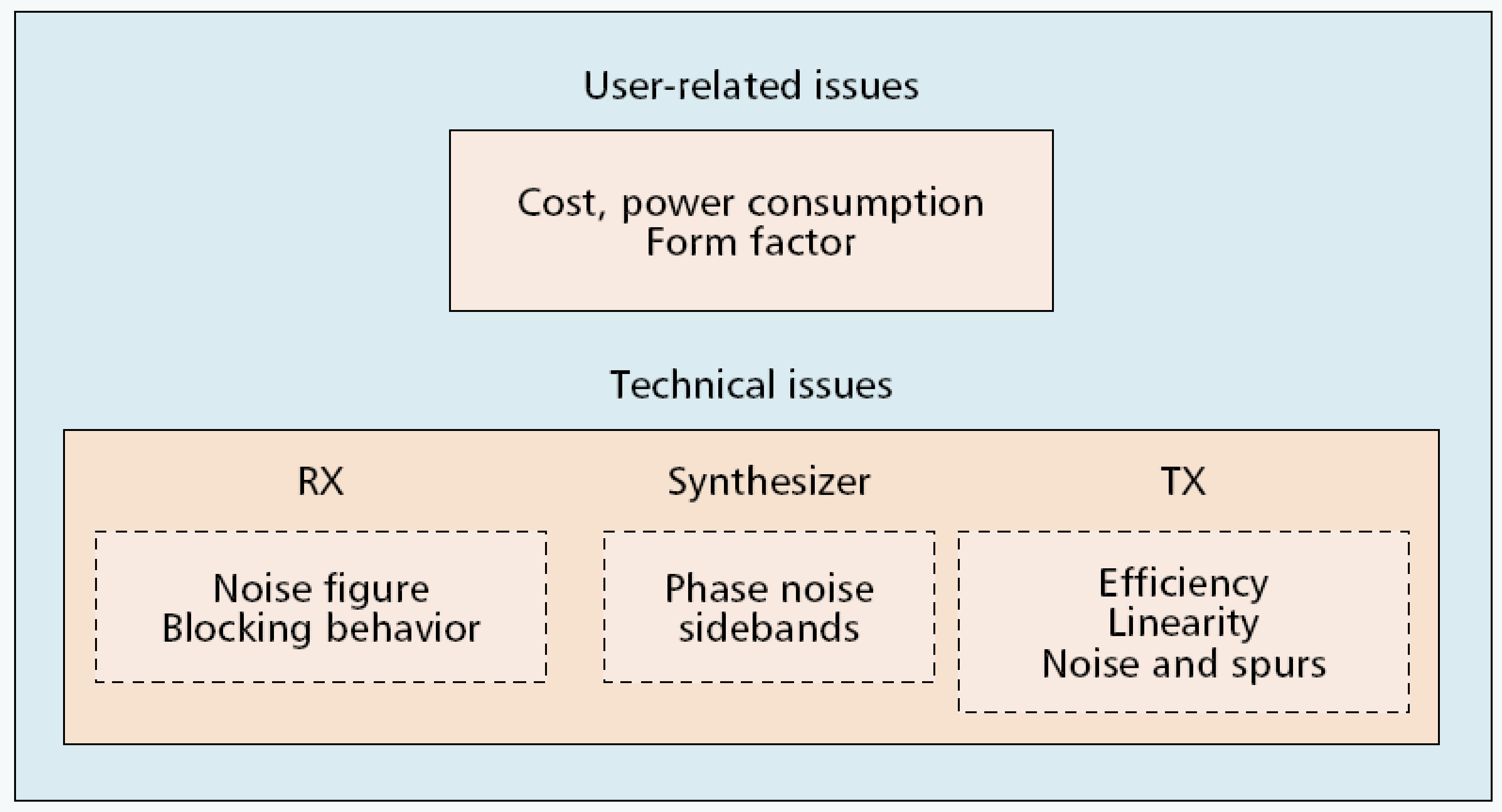
Variable gain amplifier (VGA)

Power amplifier (PA)

Voltage controlled oscillator (VCO)

Not a complete list

RF transceiver design parameters



User-related issues

Cost, power consumption
Form factor

Technical issues

RX

Noise figure
Blocking behavior

Synthesizer

Phase noise
sidebands

TX

Efficiency
Linearity
Noise and spurs

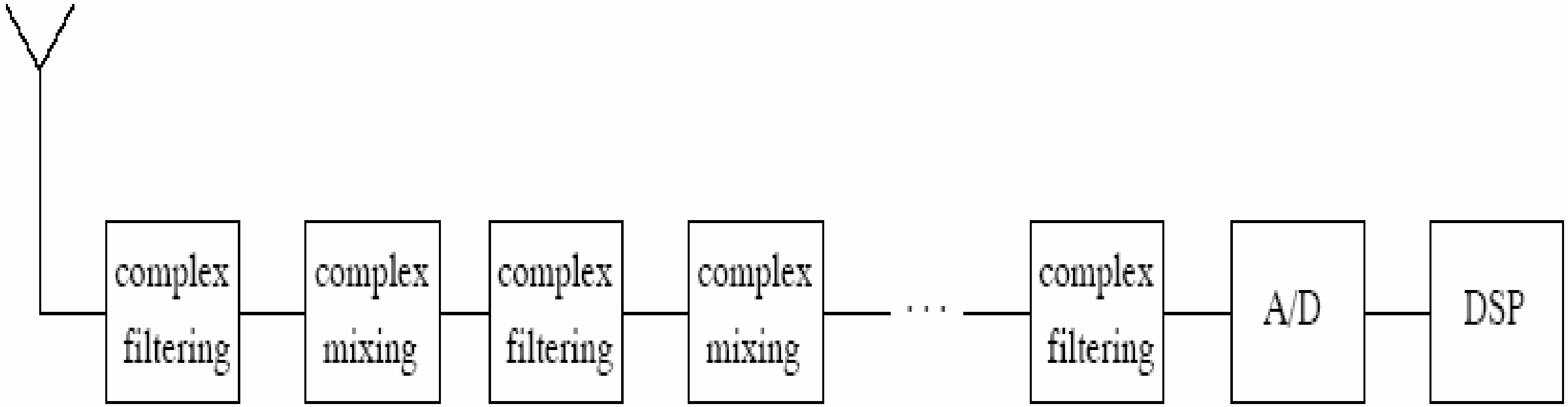
Image: B. Razavi

Basic function of a receiver front-end

What do we want of a receiver front-end:

Select and receive a small desired channel or signal among many interferers: we need ***gain***, ***selectivity*** and ***frequency-conversion*** (for digital-processing at low frequencies).

Generic receiver architecture



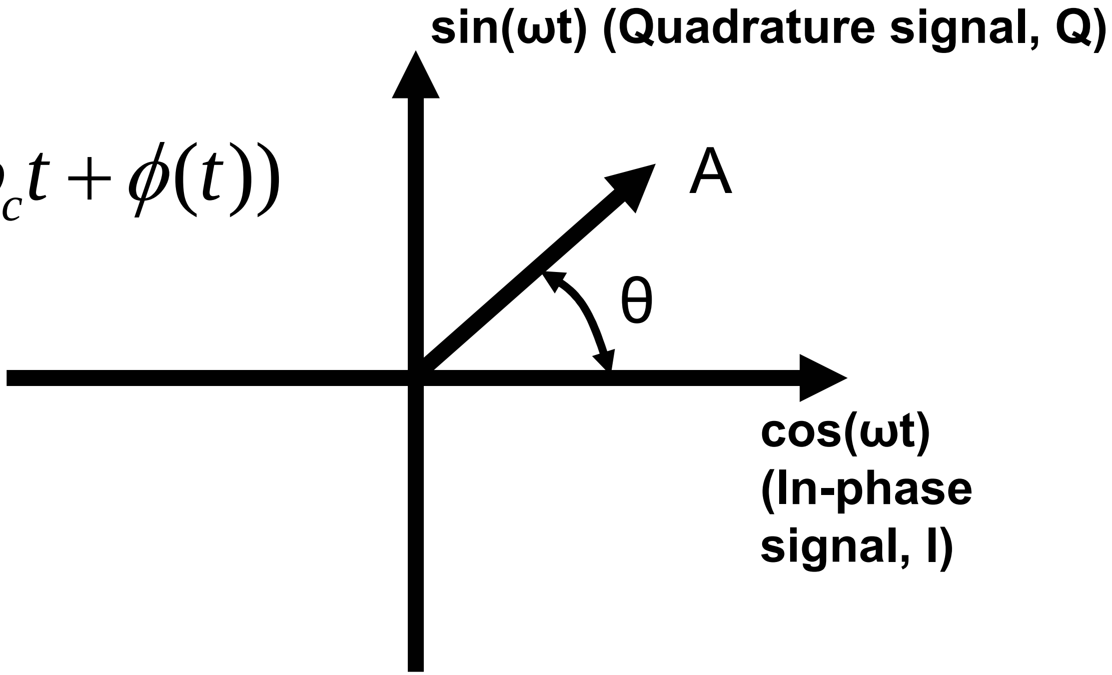
Practically the basis for every receiver architecture

Source: A. Leeuwenburgh

General RX aspects

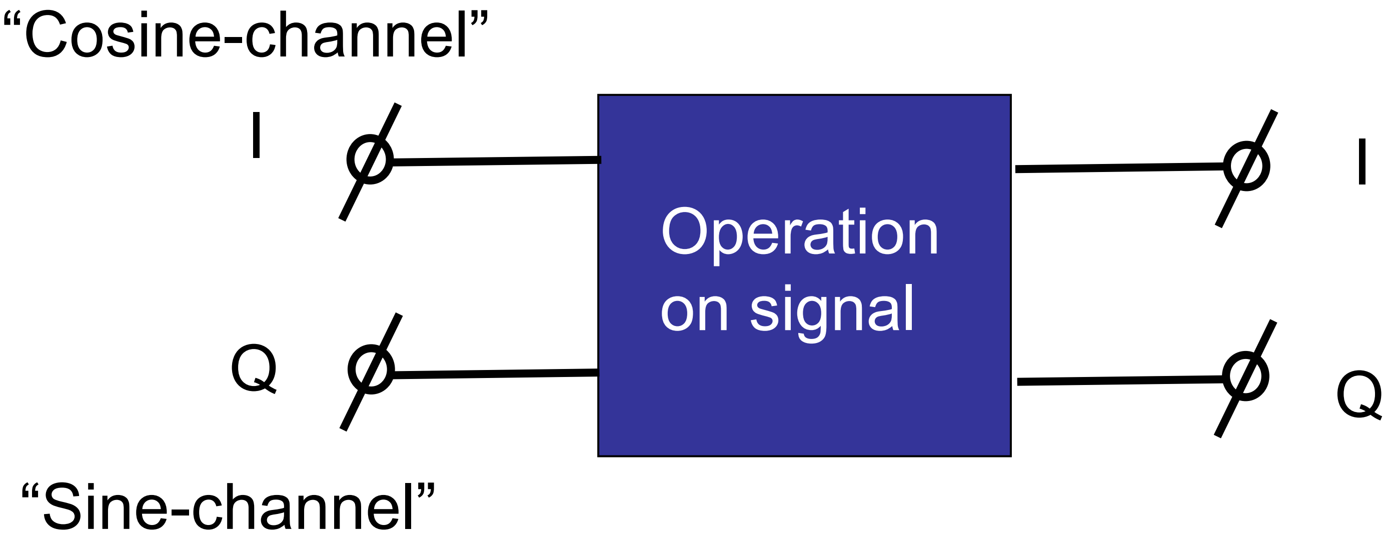
Quadrature signals: complete signal description

$$s(t) = A_c \cos(\omega_c t + \phi(t))$$



$$s(t) = A_c \cos(\phi(t))\cos(\omega_c t) - A_c \sin(\phi(t))\sin(\omega_c t)$$

Complex signal processing

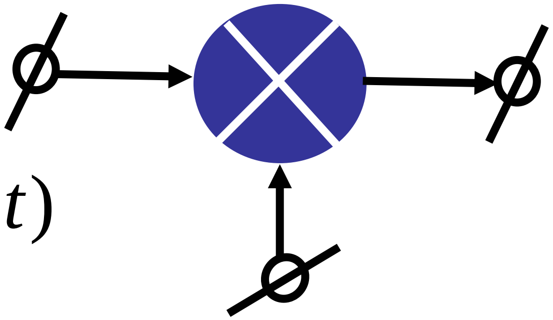


Quadrature signals needed for complete signal description

Frequency conversion: mixing frequencies

Radio frequency (RF) input

Intermediate frequency (IF) output



$$IF_{out} =$$

$$\cos((\omega_{RF} - \omega_{LO})t) +$$

$$\cancel{\cos((\omega_{RF} + \omega_{LO})t)}$$

$$RF_{in} = \cos(\omega_{RF} t)$$

Local oscillator (LO) output

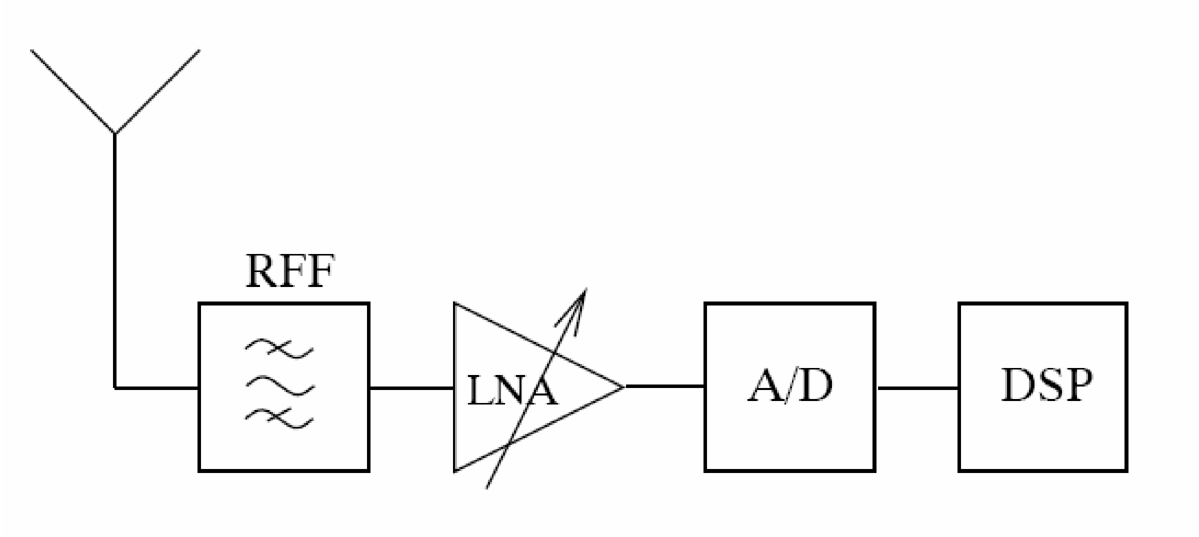
$$LO_{in} = 2\cos(\omega_{LO} t)$$

Filter

RF Sampling

RF sampling (I)

Digitization almost directly at the antenna



Currently, still not feasible / cost-effective given normal constraints for power consumption and cost.

Source: V. Vidojkovic

RF sampling (II)

- For example, for a Digital European Cordless Telephone (DECT) system, which is working at 1.9 GHz:
  - An A/D converter is needed with at least a sampling rate of the nyquist frequency (3.8 GHz) and 14 bits resolution.

When RF sampling becomes cost-effective it will be the most flexible “software-defined” receiver implementation

Super-heterodyne receiver

Super-heterodyne receiver (I)

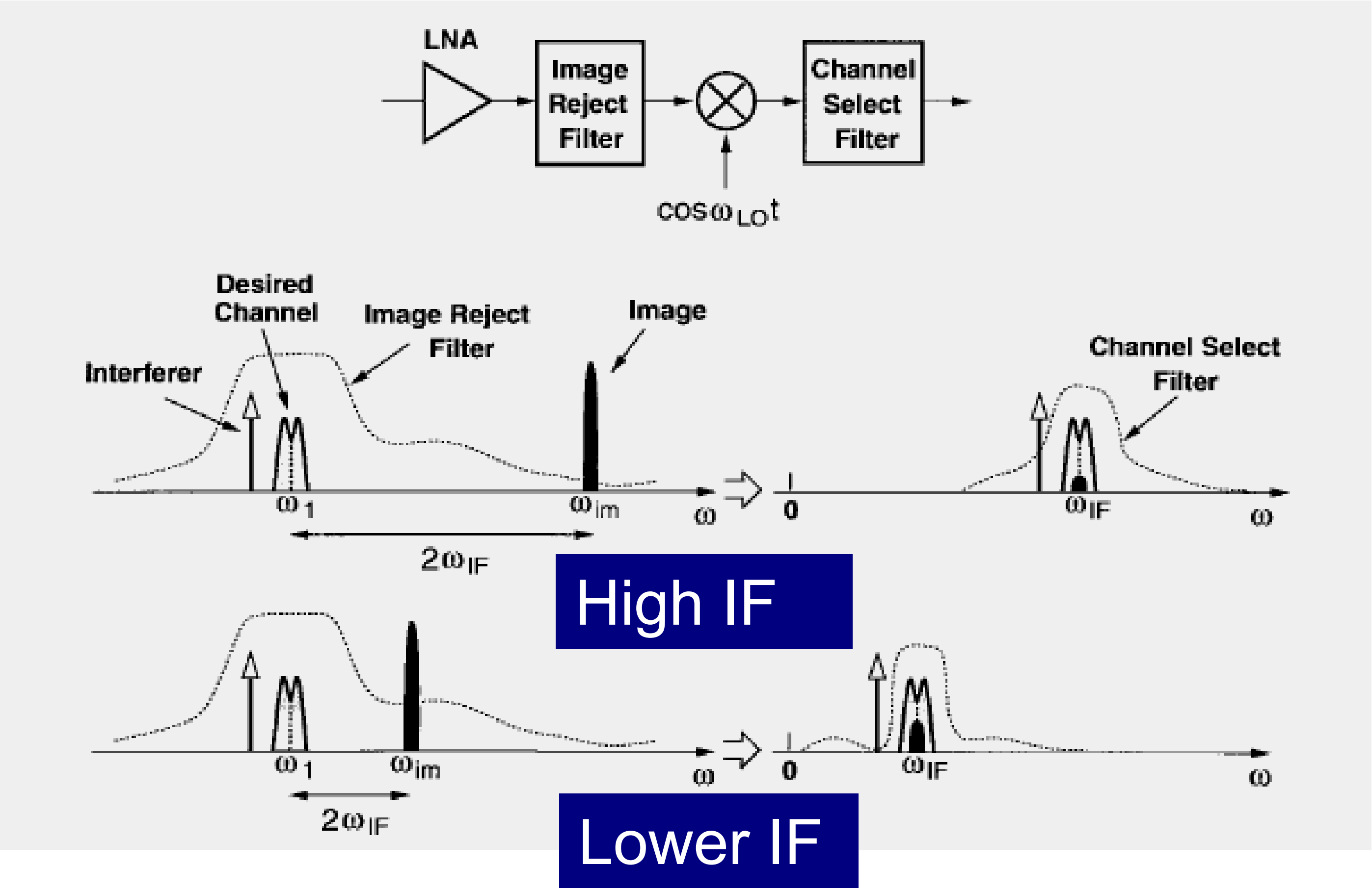
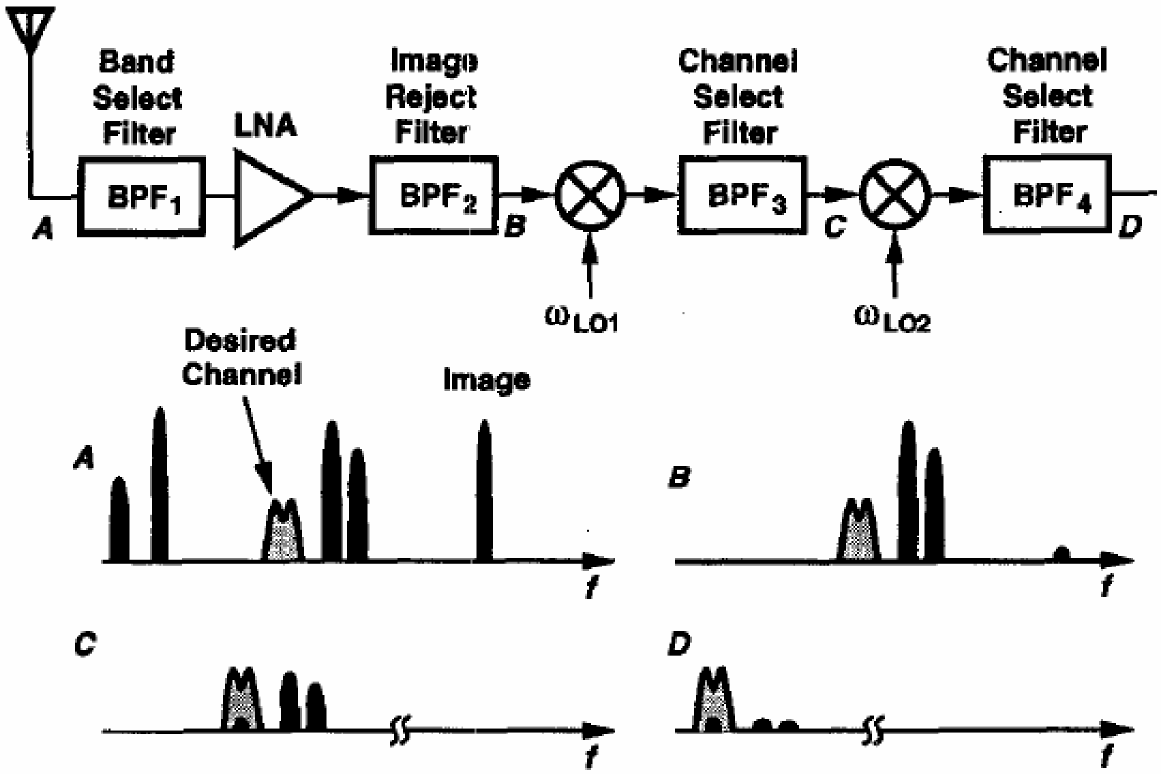


Image: B. Razavi

Super-heterodyne receiver (II)



An example of a double-conversion receiver (two IFs)

Image: B. Razavi

Advantages & Disadvantages
Super-heterodyne receiver

Advantages:

- Excellent selectivity: selection of small signals in the presence of strong interfering signals (interferers).

Disadvantages:

- Bulky external RF and IF filters normally needed: expensive, pin-count, power-hungry (50 Ohm interface)

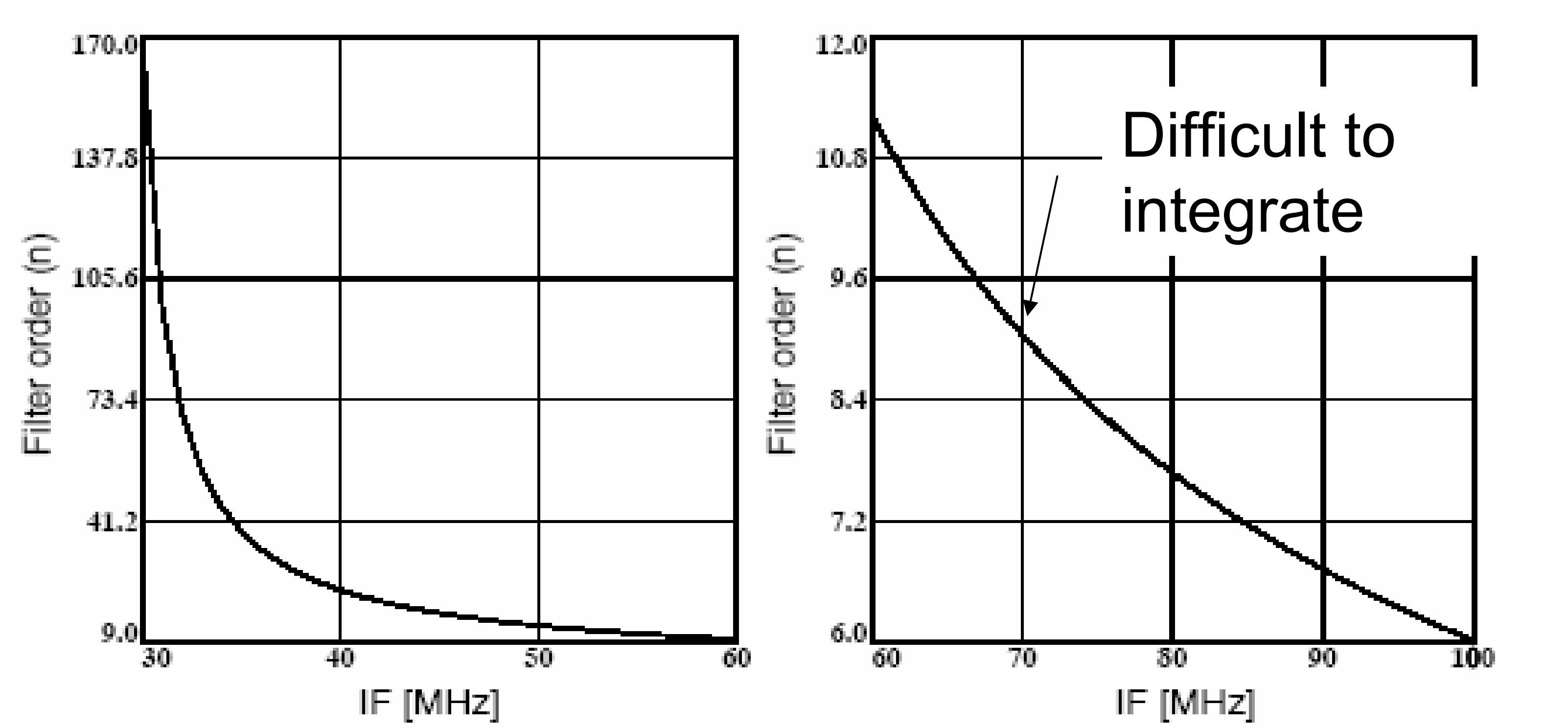
- Several spurious frequency components due to the frequency conversions: good frequency planning needed.

Source: V. Vidojkovic

Example of requirements of a DECT RF filter versus IF

$$f_{image} = f_{wanted} - 2IF$$

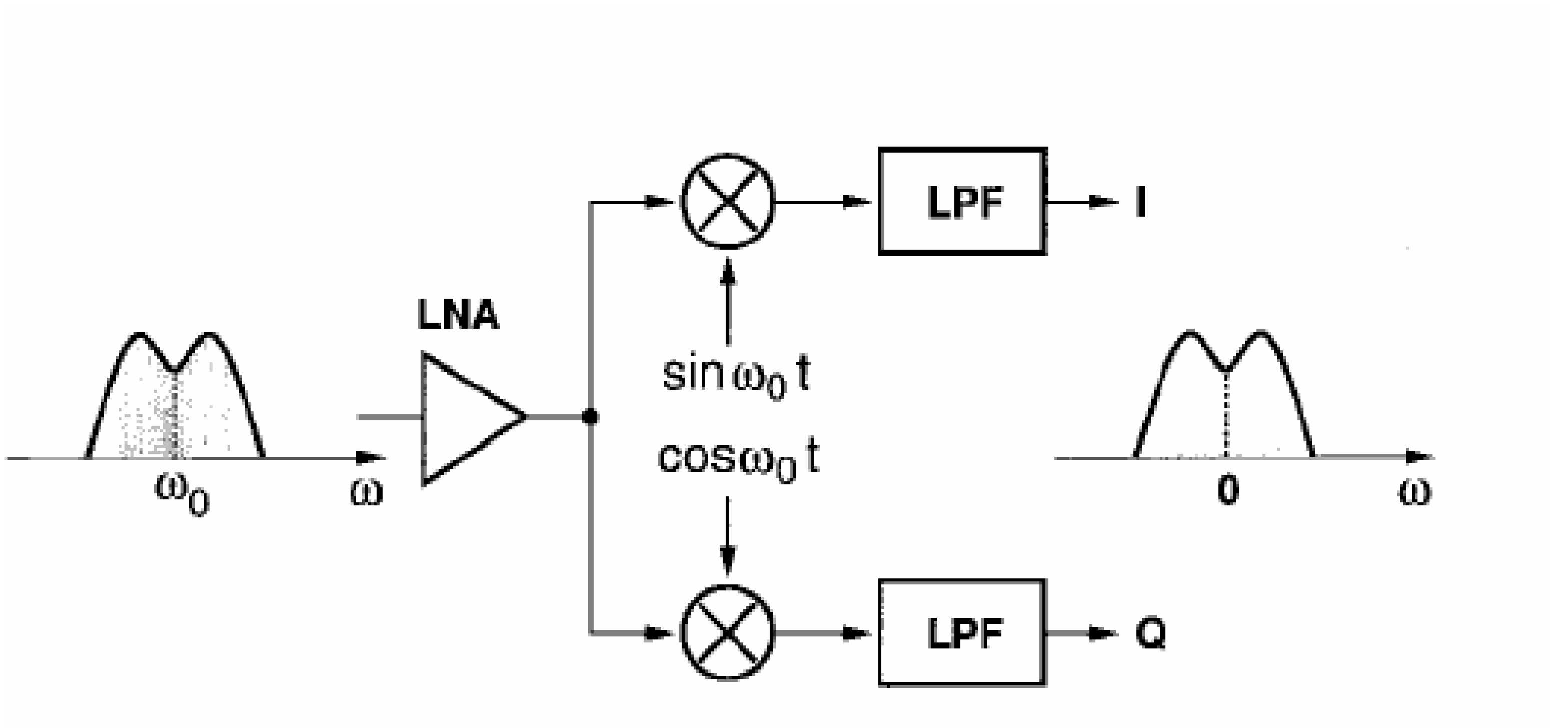
DECT works at 1.9 GHz
Assume 20 dB image suppression, and B=100 MHz



Difficult to integrate

Direct-Conversion receiver

Direct-conversion receiver



Wanted channel directly converted to baseband (“0 Hz”)

Image: B. Razavi

Advantages of direct-conversion

For phase and frequency modulated signals, direct-conversion requires I/Q signals.

Advantages:

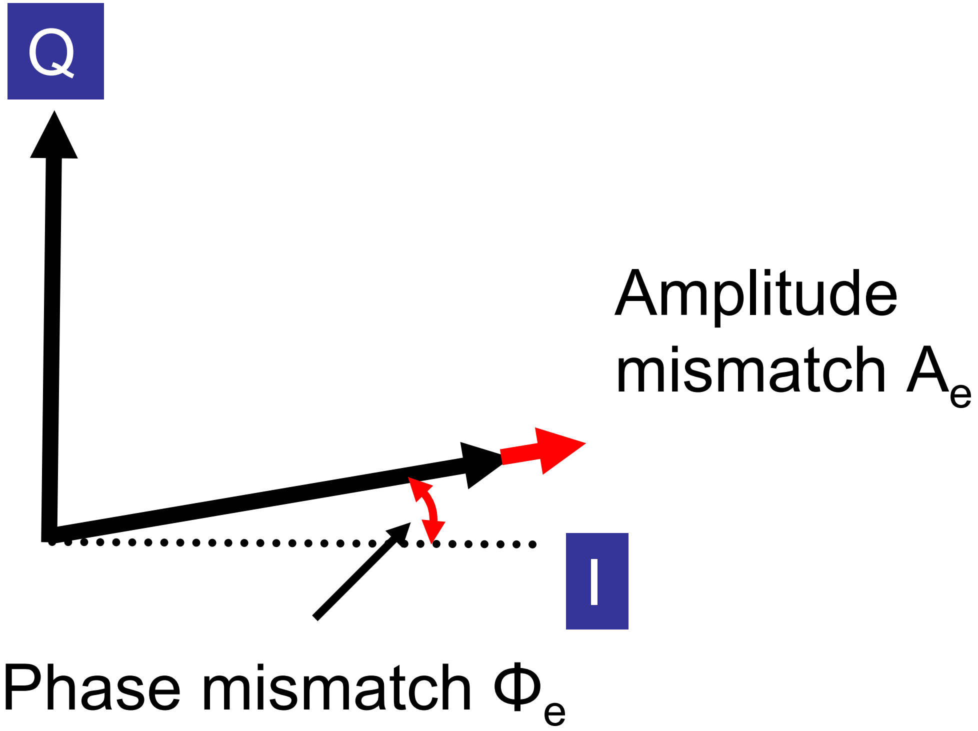
- No image, since the wanted signal is its image (ω_{IF}=0)

- The IF filter in a super-heterodyne receiver is replaced by low-pass filters

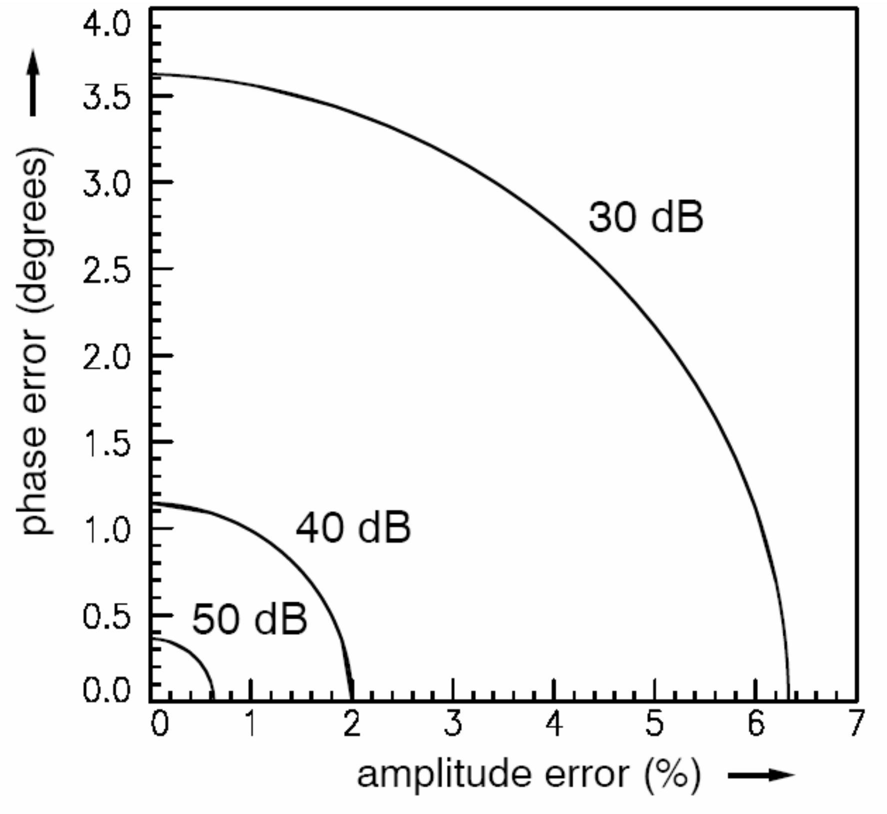
- Low-pass filters are easy to integrate; in general direct-conversion (Zero-IF) receivers allow a high level of integration.

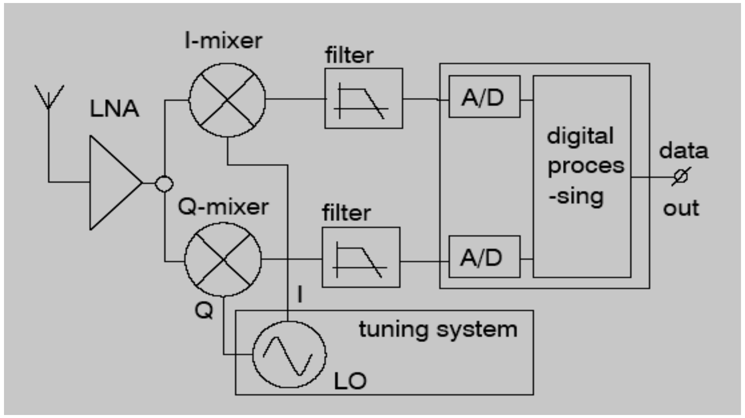
Disadvantages / design issues of direct-conversion

- Cross-talk (image-problem) when there is amplitude or phase mismatch between I and Q channel.



Disadvantages / design issues of direct-conversion: I/Q mismatch





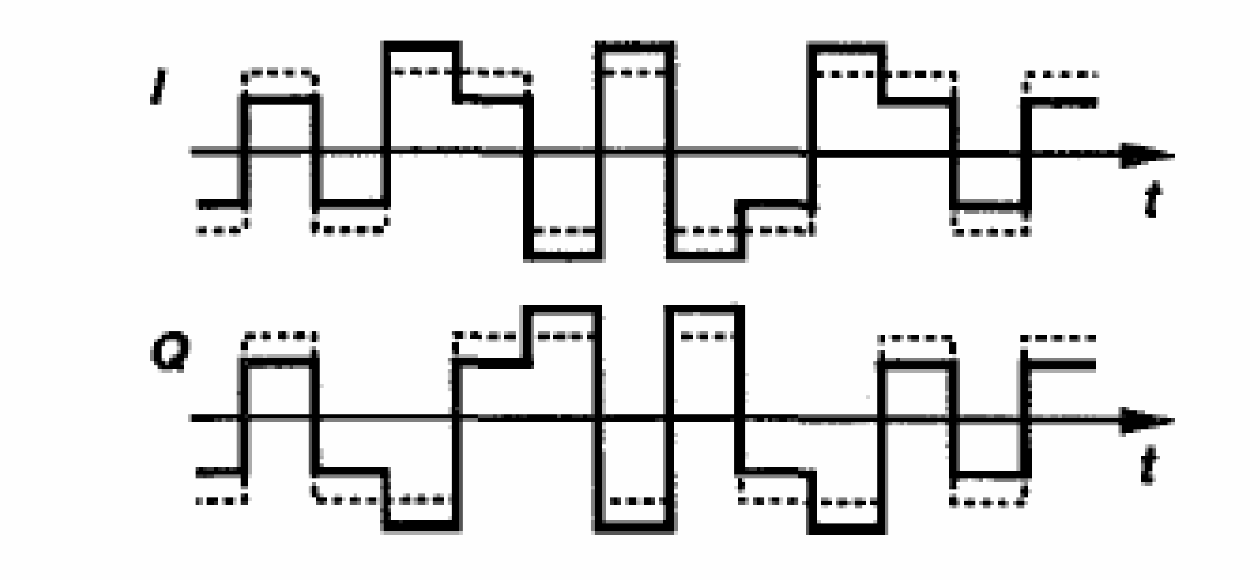
$$IRR \approx 10\log\left(\frac{4}{A_e^2+\phi_e^2}\right)$$

Amplitude error

Phase error

Effect of I/Q mismatch

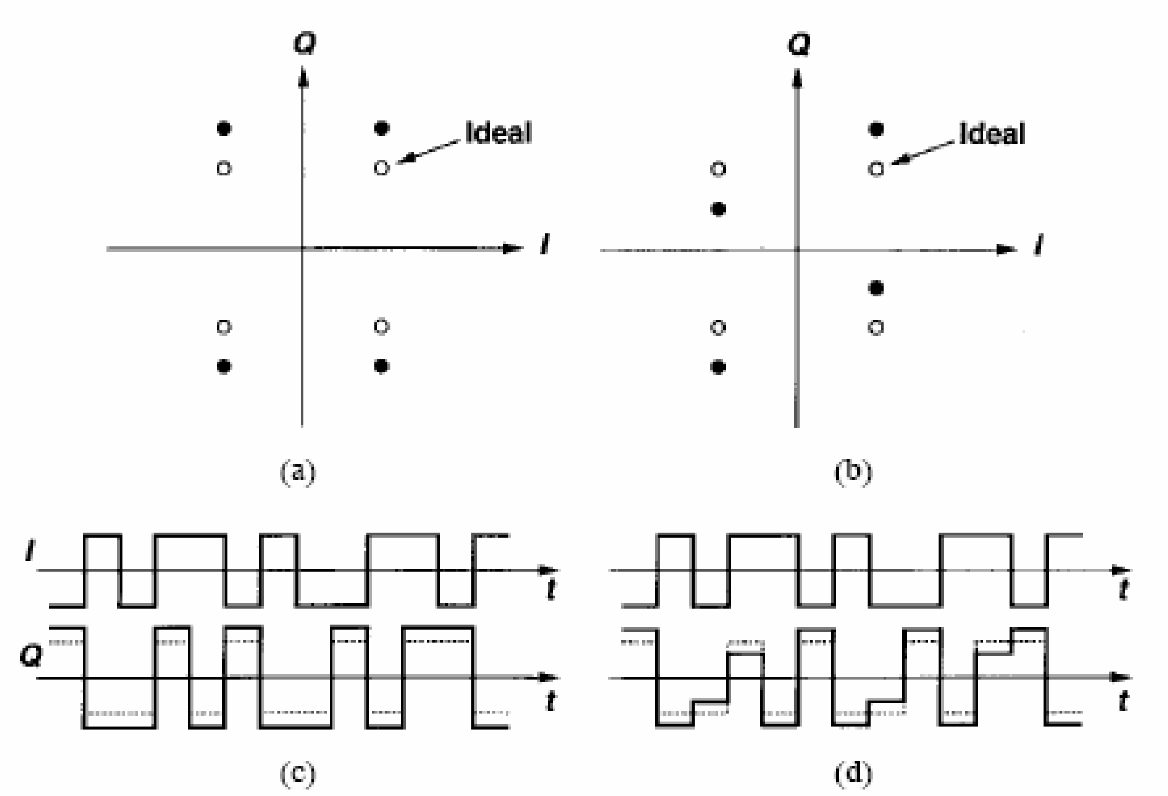
Demodulated QPSK data



For example, phase imbalance yields cross-talk in the demodulated quadrature signal, thus lowering the SNR (BER) of the received signal.

Image: B. Razavi

Effect of I/Q mismatch on constellation diagram for QPSK modulation

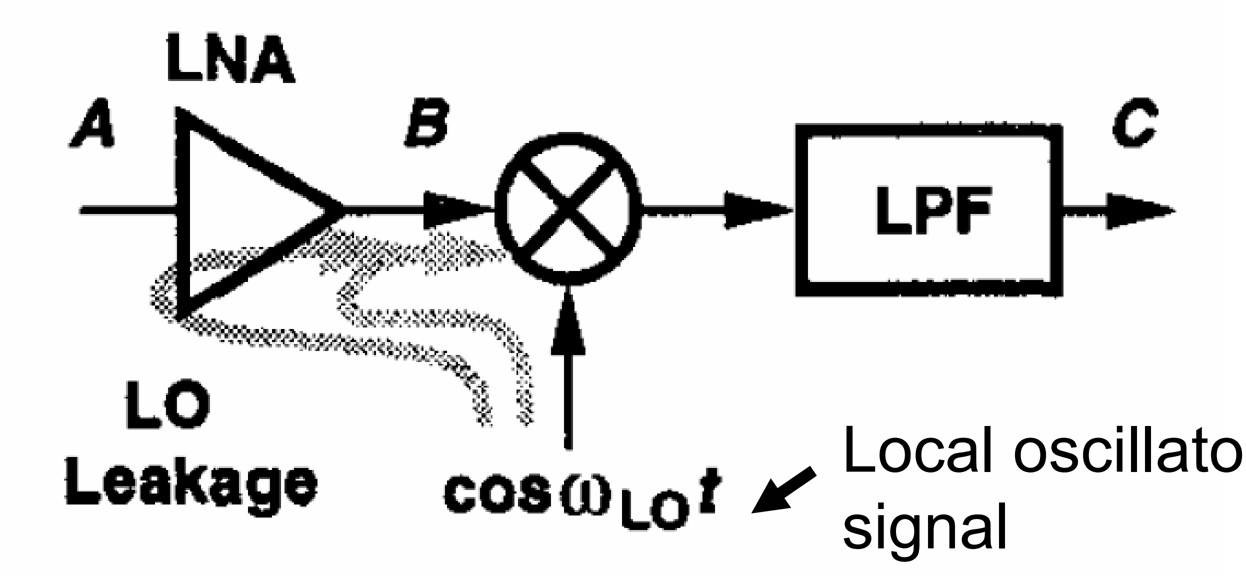


Effect of gain mismatch

Effect of phase mismatch

Image: B. Razavi

Disadvantages / design issues of direct-conversion: LO leakage

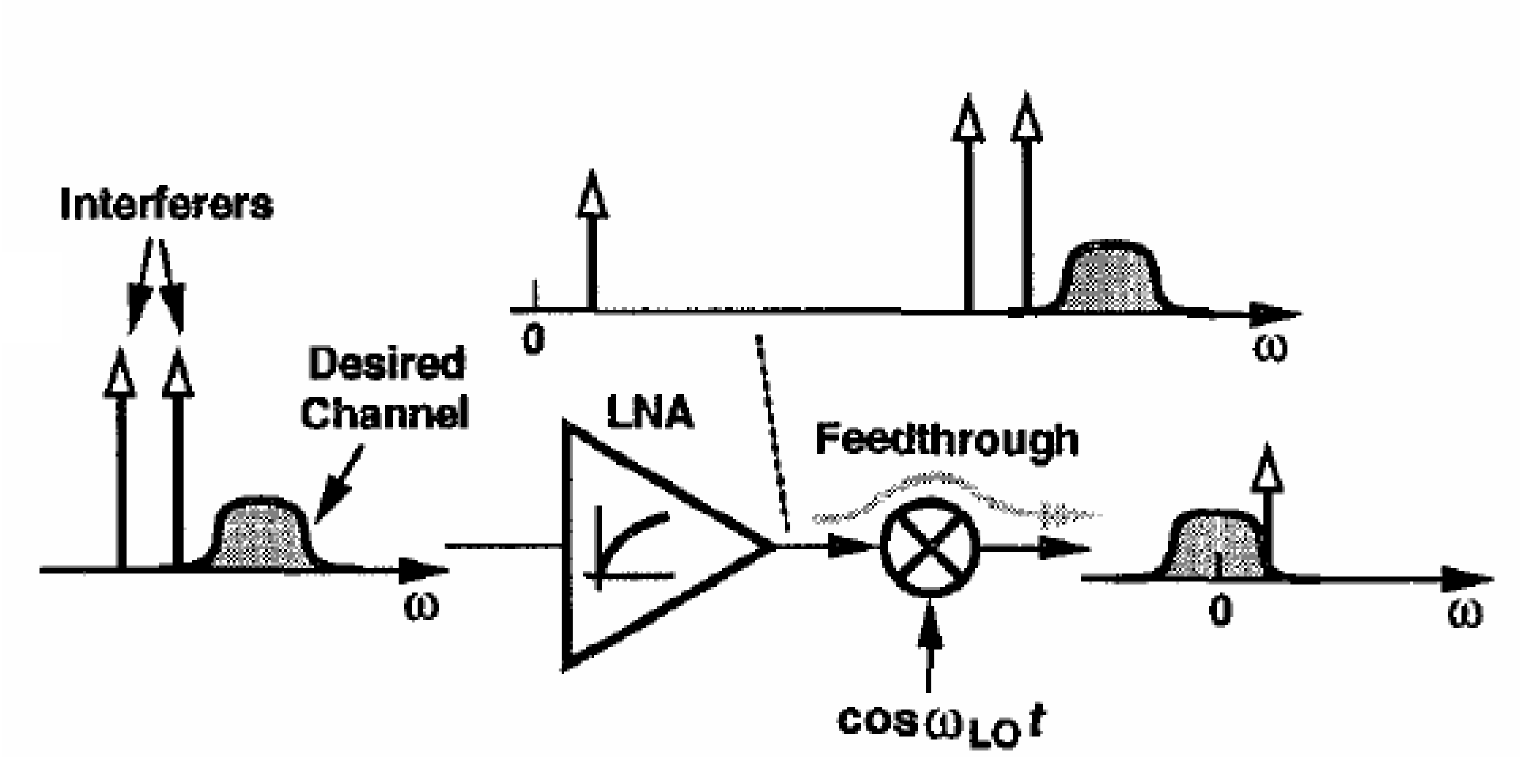


Local oscillator signal

The local oscillator signal leaks to RF input port of the mixer (LO leakage), which causes self-mixing. This results in (modulated) DC components (that cannot be removed by AC-coupling if there is a lot signal content (energy) located around DC.

Image: B. Razavi

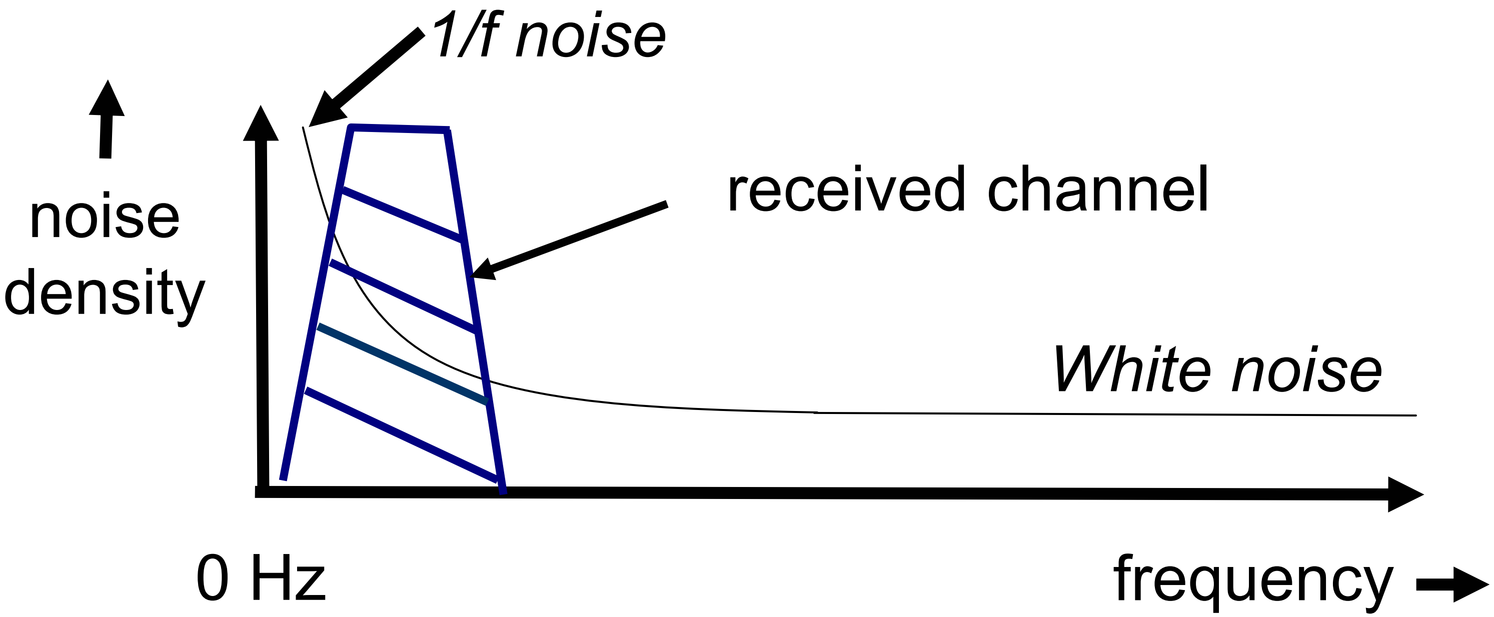
Disadvantages / design issues of direct-conversion: IM2 products



Even-order distortion creates low-frequency beat notes that can be passed on by the mixer in case of mismatch

Image: B. Razavi

Disadvantages / design issues of direct-conversion: 1/f noise



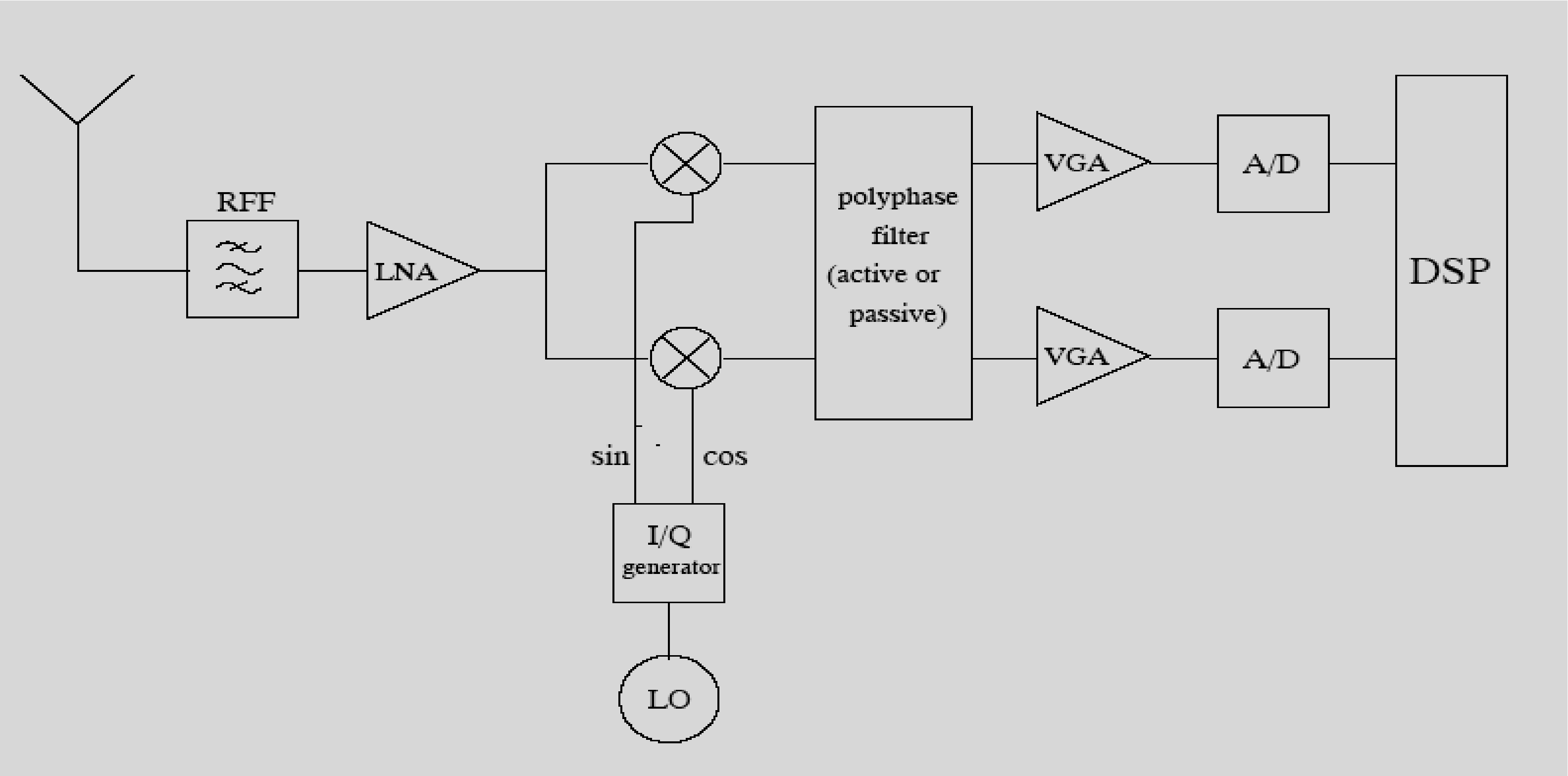
Especially, for CMOS transceivers, 1/f noise can pose big problems for the received channel that is down-converted in the middle of the 1/f noise.

Direct-conversion: frequently used

- Despite the many design challenges direct-conversion receivers face, they are used in many products.
- The high level of integration it allows is one of the main driving forces behind its use.
- Especially in consumer electronics, costs are a dominant factor; external components are very expensive and influence the bill-of-material (BOM) in a negative sense.

Low-IF receivers

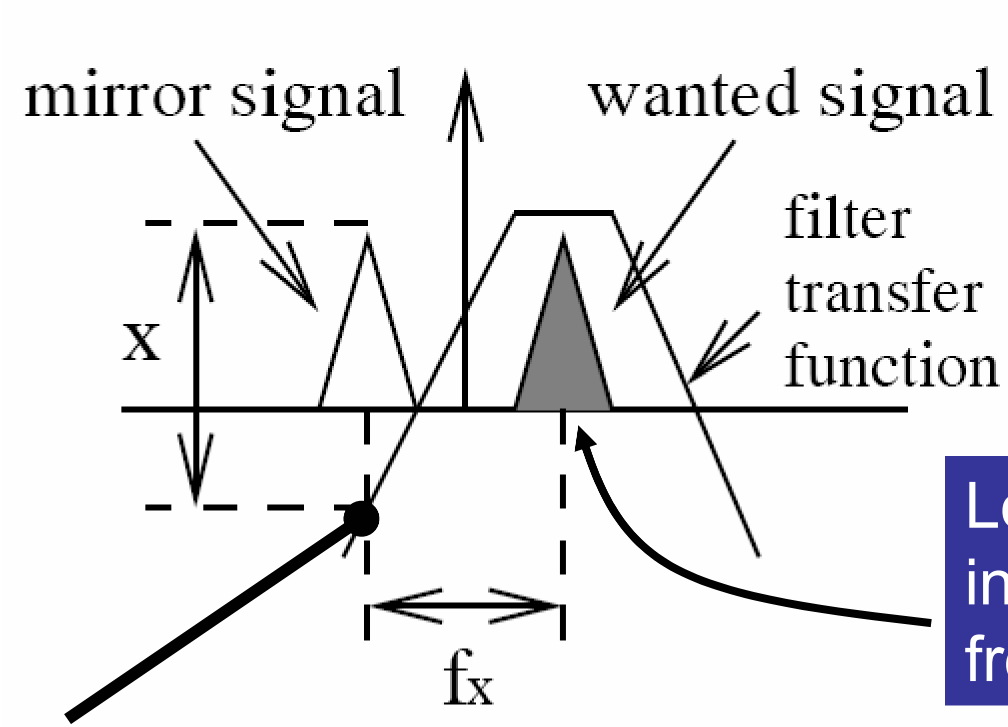
Low-IF receiver



Wanted channel is converted to a low, non-zero IF.

Image: V. Vidojkovic

Image is suppressed in a Low-IF receiver by a poly-phase filter



Low-intermediate frequency

A poly-phase filter (normally I- and Q-phase) can have an asymmetric transfer function with respect to 0 Hz.

Advantages Low-IF receiver

Advantages:

- Image is suppressed by a poly-phase filter, which can be integrated. Because of matching, 30-35 dB image suppression is typical.

- The IF-frequency is not 0 Hz, hence the influence of 1/f noise in the receiver chain is less.

- A high-pass filter may be used after the mixer to remove unwanted DC components, assuming the used modulation allows removal of part of the energy in the spectrum around DC.

Disadvantages/ design issues of a low-IF receiver

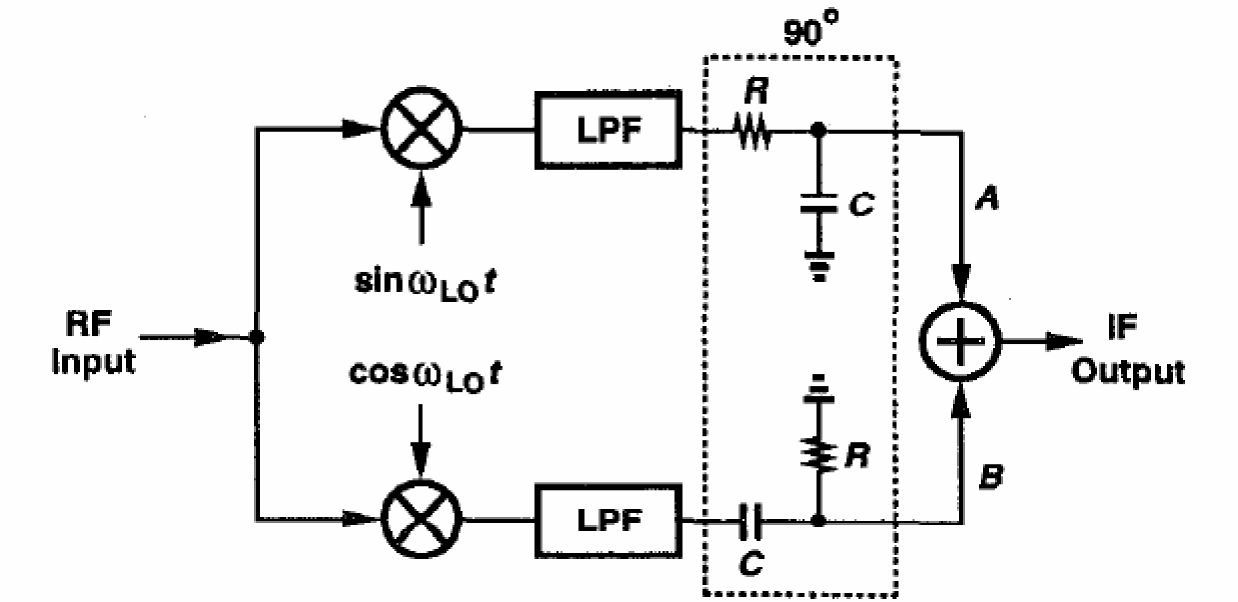
disadvantages:

- Image suppression is limited by I/Q matching (same problem as direct-conversion architectures).
- Poly-phase filters may be power-hungry (relative compared to low-pass filters)
- Poly-phase filters may require a lot of chip area (large capacitors, because of the low-IF).
- Even-order distortion components may still produce unwanted beat notes in the wanted channel, after down-conversion

Image-reject architectures

Hartley image-reject receiver

Summed signal is free from image under perfect matching conditions.



The main draw-back is its high sensitivity to mismatches between the two signal paths.

Image: B. Razavi

Spectra in Hartley architecture

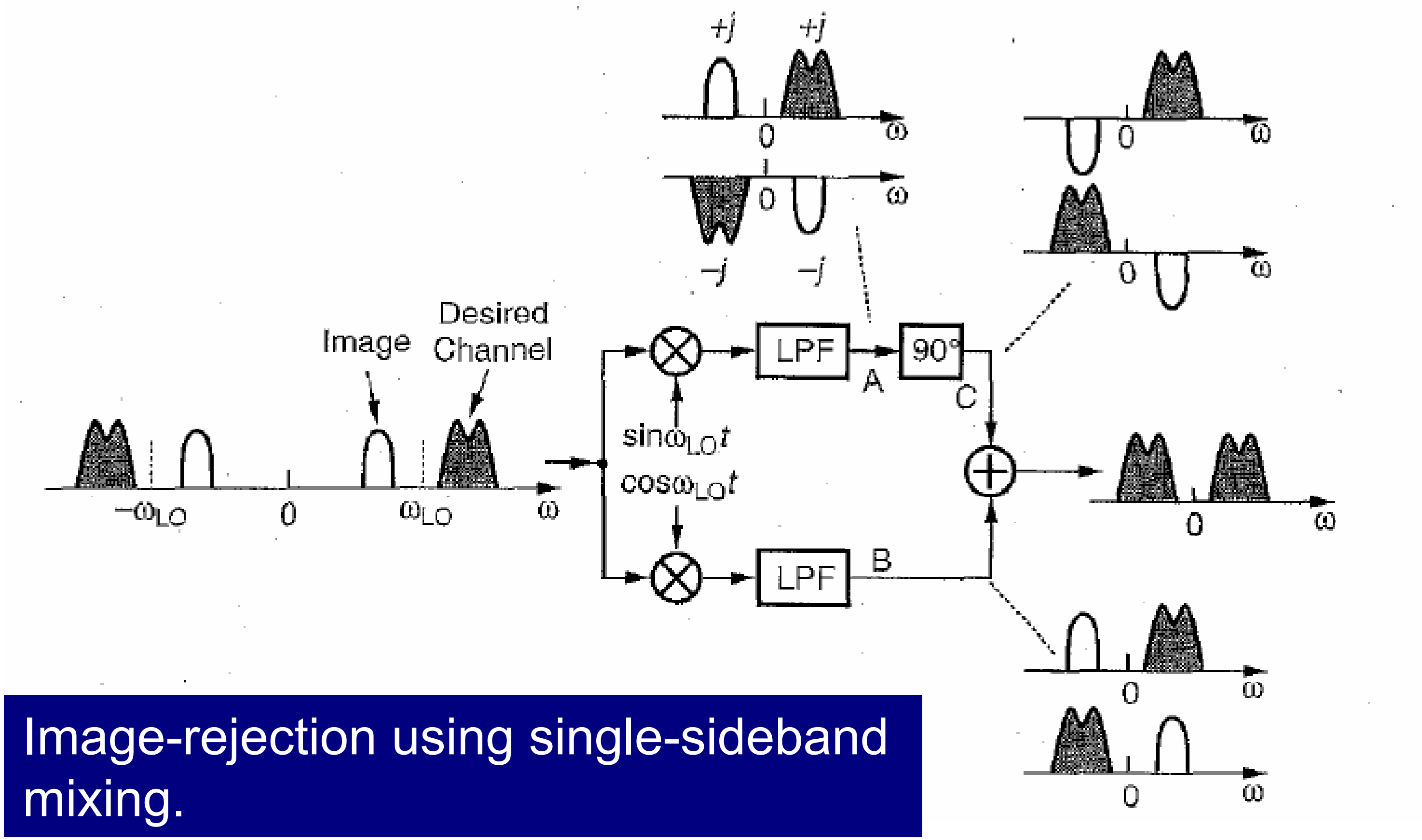
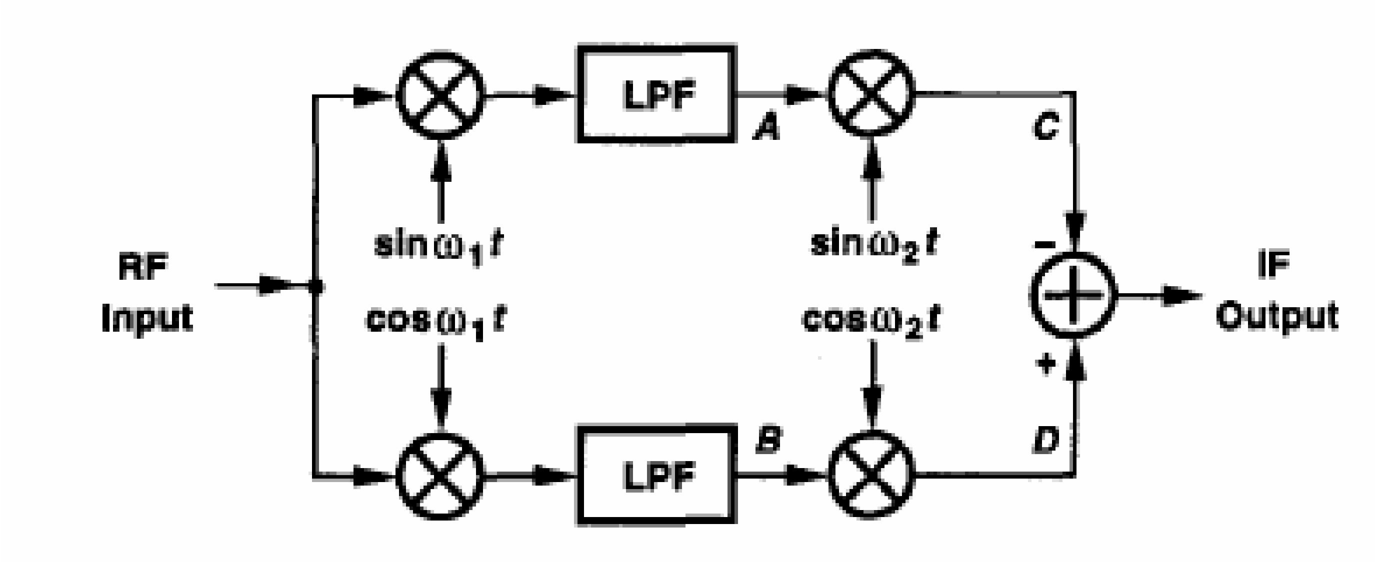


Image-rejection using single-sideband mixing.

Image: B. Razavi

Weaver image-reject receiver

RC-CR network which is present in the Hartley receiver architecture is avoided by a second time quadrature mixing.



The architecture is still sensitive to I/Q mismatch and requires two LOs.

Image: B. Razavi

Spectra in Weaver architecture

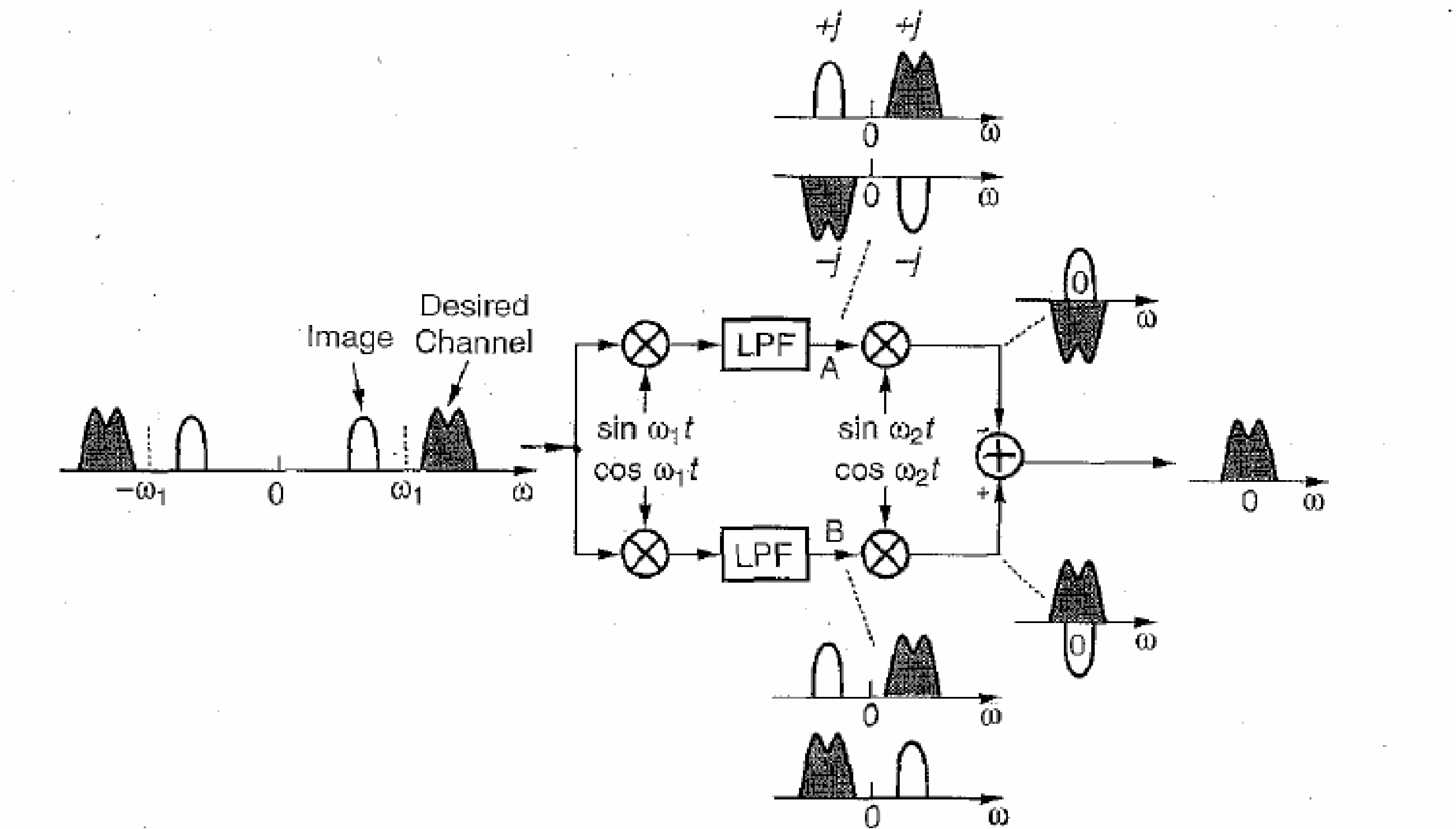
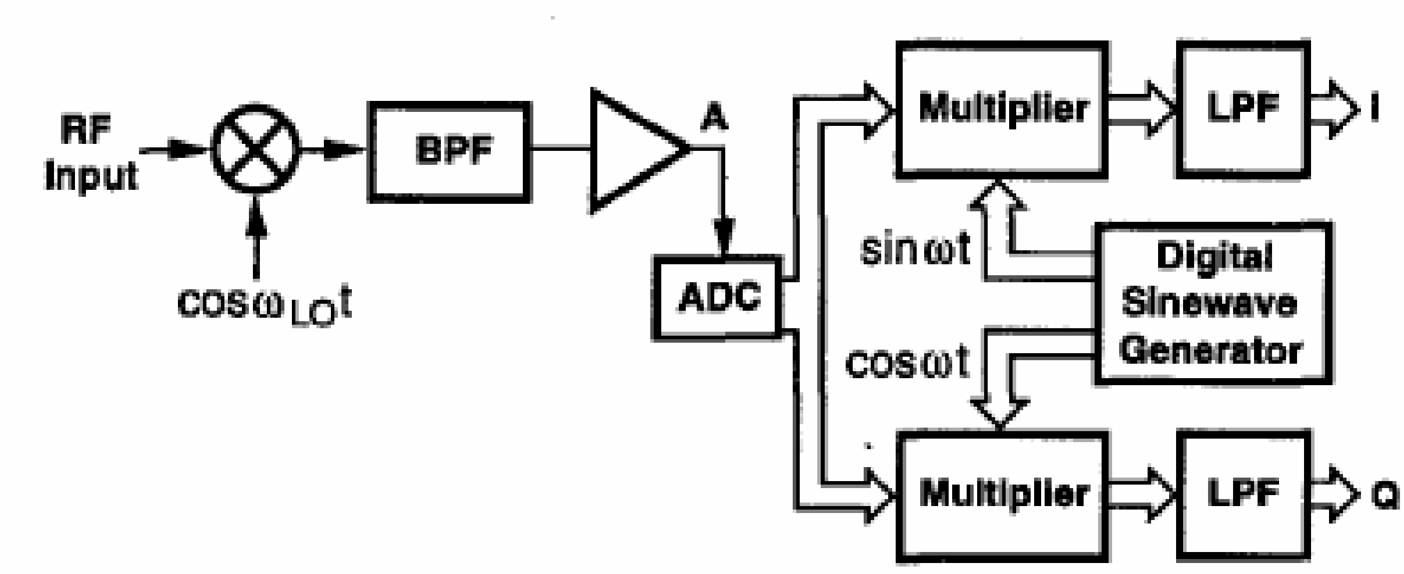


Image: B. Razavi

Digital-IF Receiver

Digital-IF Receiver

Received signal is digitized at the IF: high A/D requirements, but e.g. possible for FM radio.

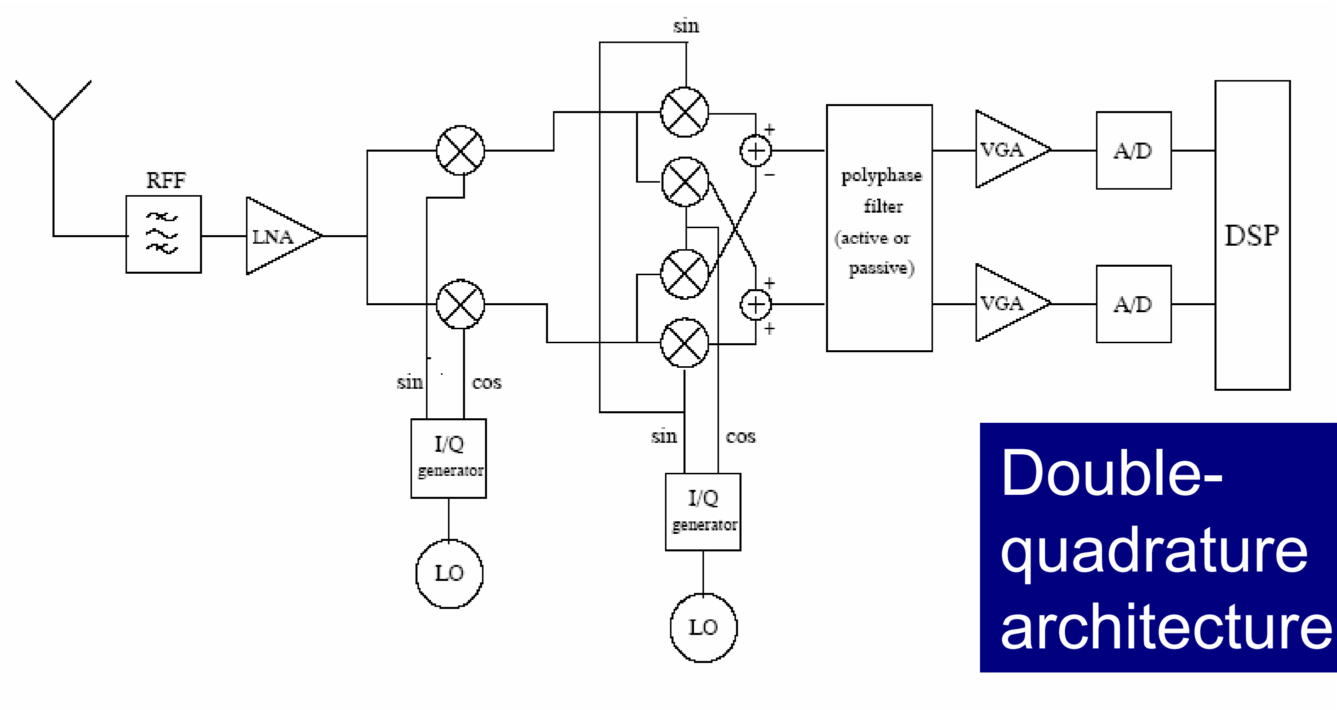


I/Q matching no issue: transferred to the digital domain

Image: B. Razavi

Examples of derivative receiver architectures

Six-mixer Low-IF architecture

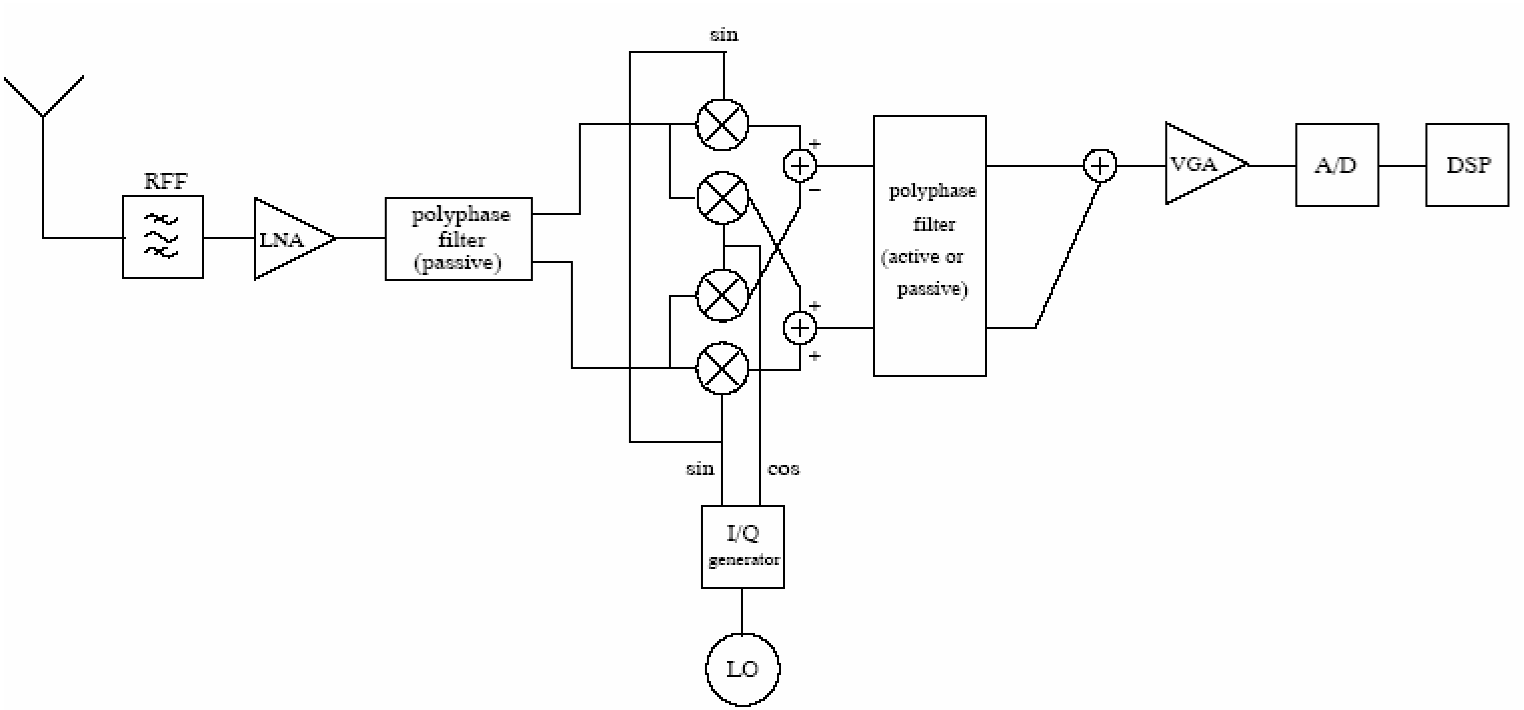


Double-quadrature architecture

IRR can be significant higher than 40 dB at the cost of more power dissipation (six mixers) and a higher complexity.

Image: V. Vidojkovic

Double-quadrature receiver with poly-phase filter in the receive path



IRR can be significant higher than 40 dB at the cost of more power dissipation and a lower sensitivity (RF poly-phase filter) and higher complexity.

Image: V. Vidojkovic

Example of architecture realized in the Mixed-signal Microelectronics group

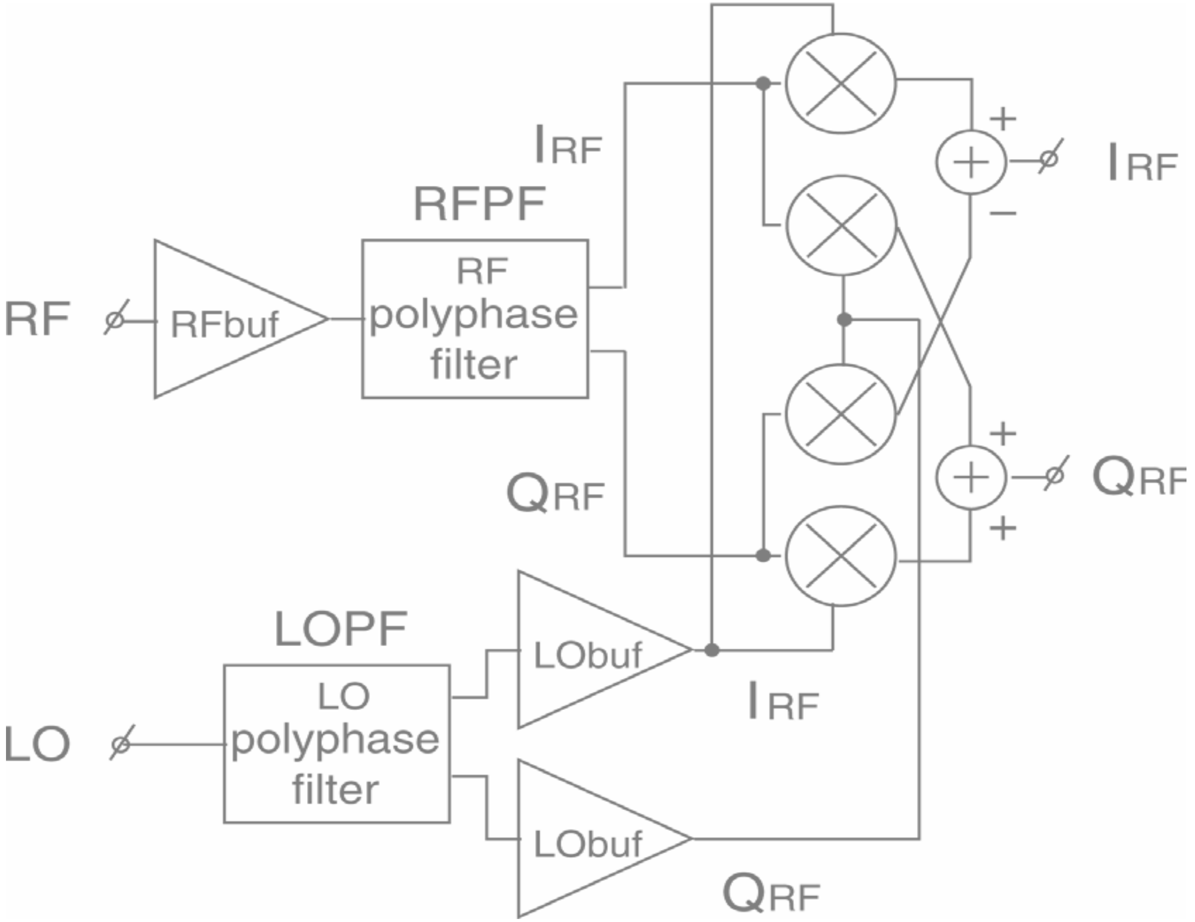


Image: V. Vidojkovic

Layout of realized chip

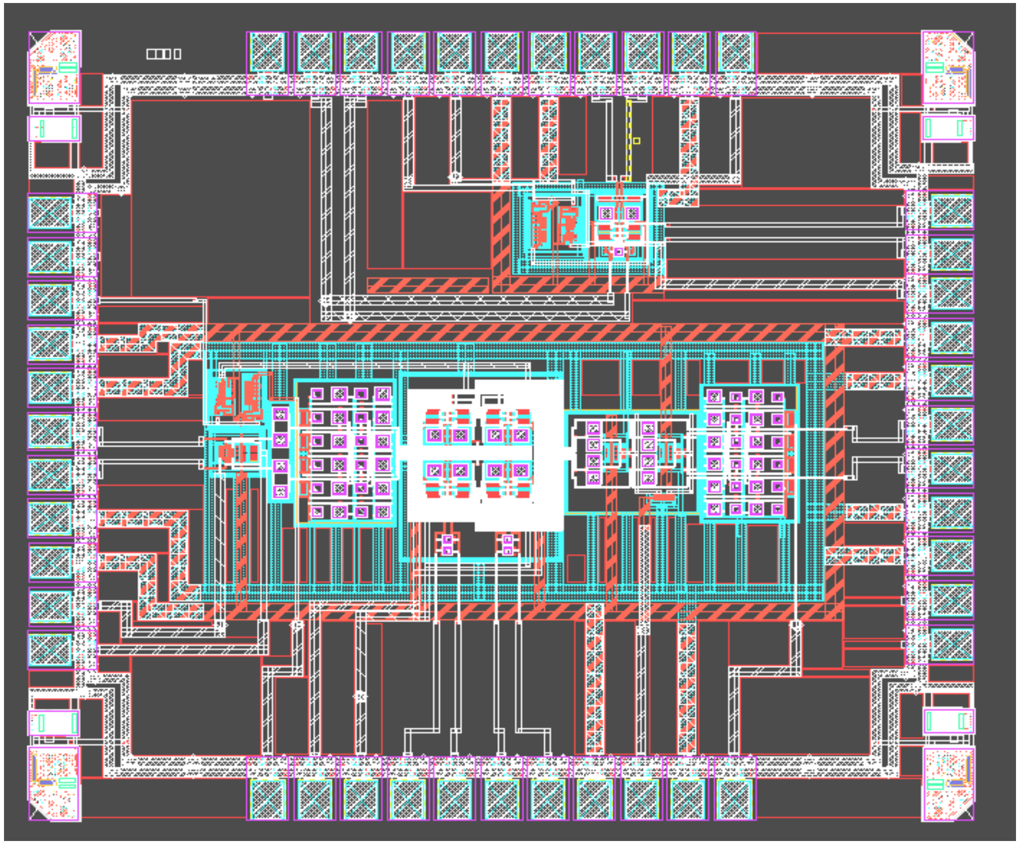
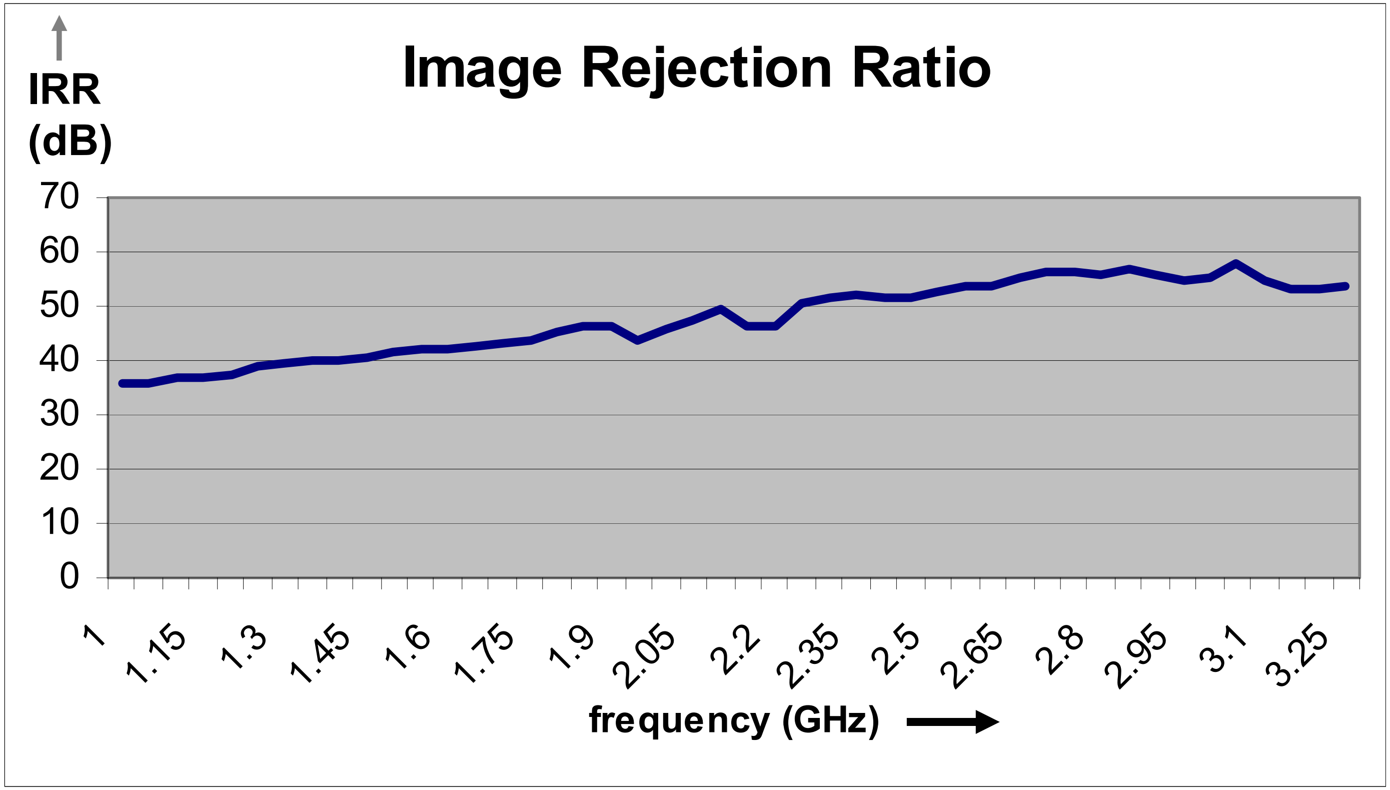


Image: V. Vidojkovic

Measured IRR of realized receiver front-end

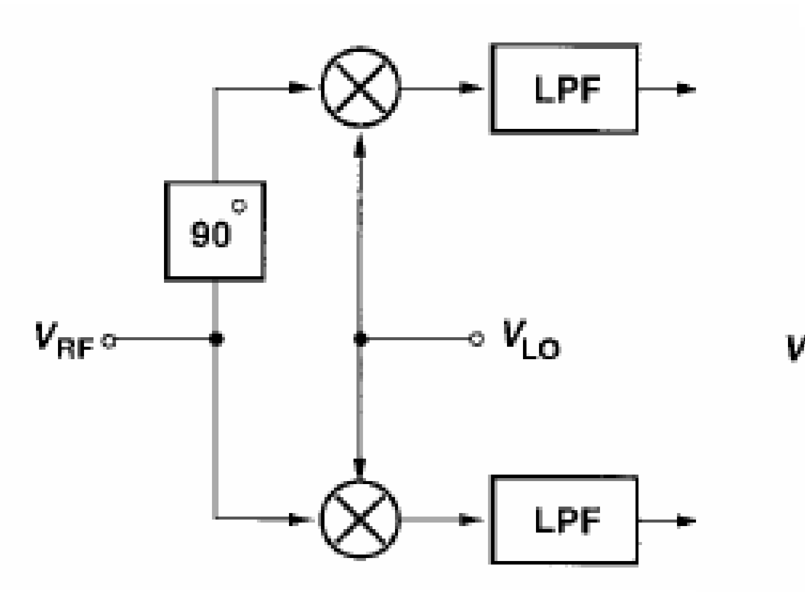


Broadband High Image Rejection

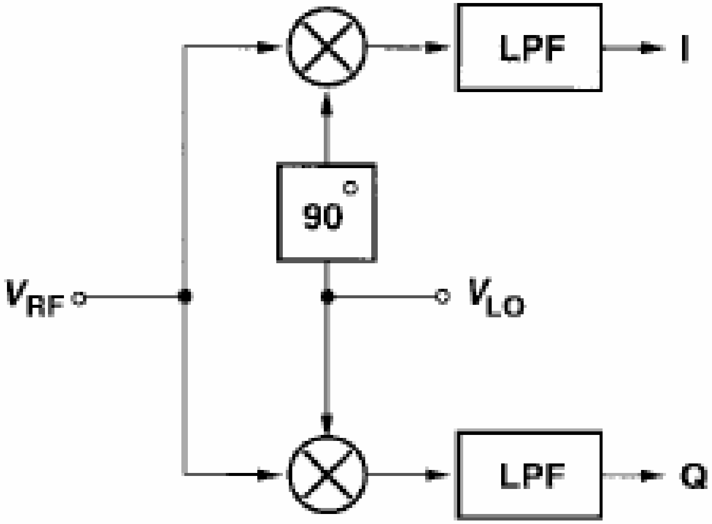
Image: V. Vidojkovic

Quadrature generation

Most often I/Q generation is done in the LO path



I/Q generation in RF path

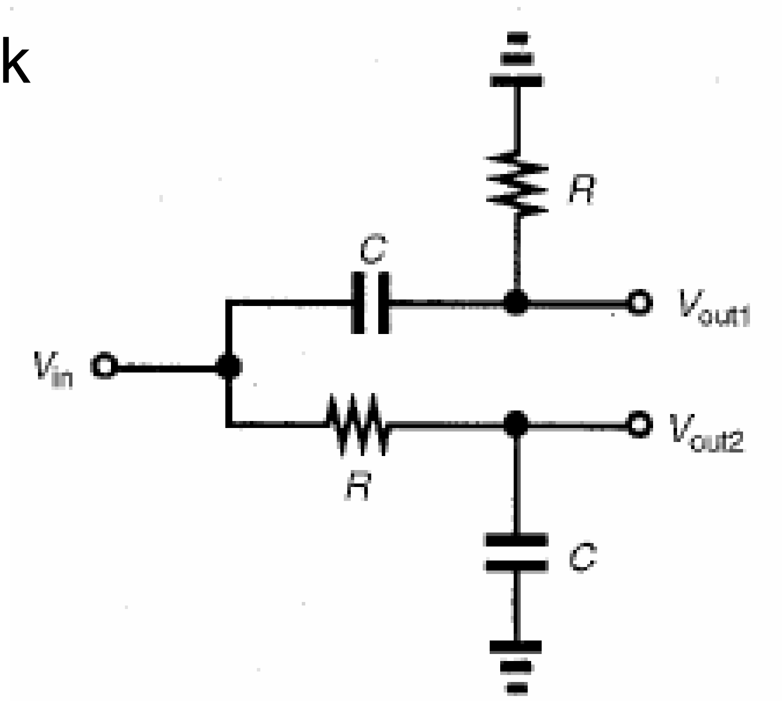


I/Q generation in LO path

Image: B. Razavi

I/Q generation (1)

RC-CR network



In-phase signal

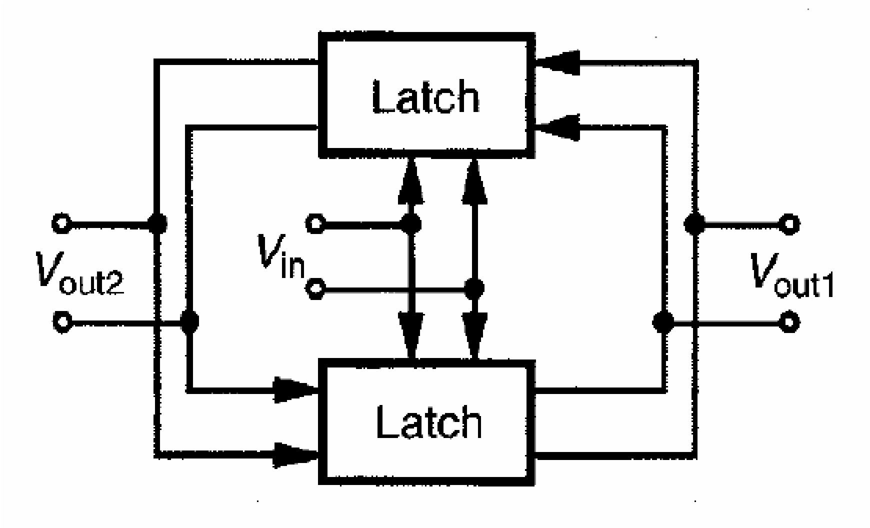
Quadrature signal

Phase-shift always 90 degrees between outputs. Amplitudes only equal for ω=1/(RC). But clipping (limiter) may be used, for example in LO path.

Image: B. Razavi

I/Q generation (2)

Using a divider-by-two and driving it at 2 f_{osc}

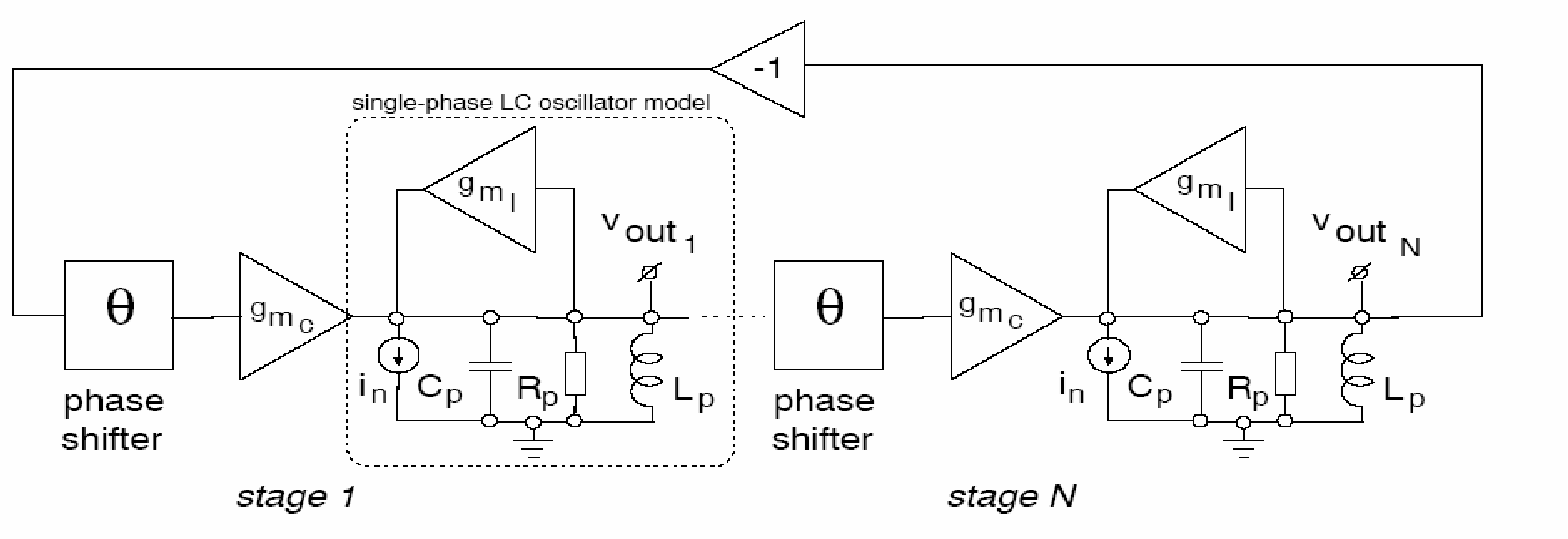


Outputs in quadrature when the input signal has a duty cycle of 50%. Two dividers can be used to improve the I/Q matching (but input signal must then be at 4 f_{osc}.

Image: B. Razavi

I/Q generation (3)

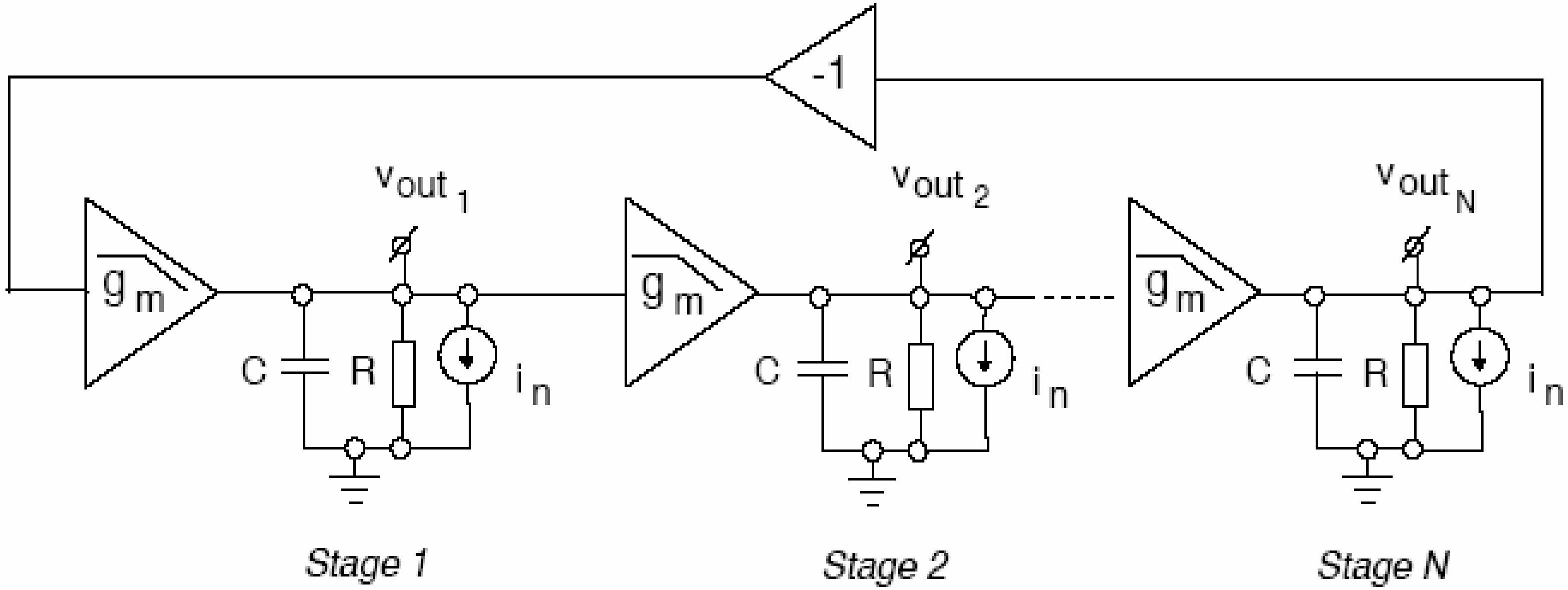
Even-stage multi-phase LC oscillators:



Inductors (2, balanced or 4 single) may require a lot chip area. Power should be compared to other solutions.

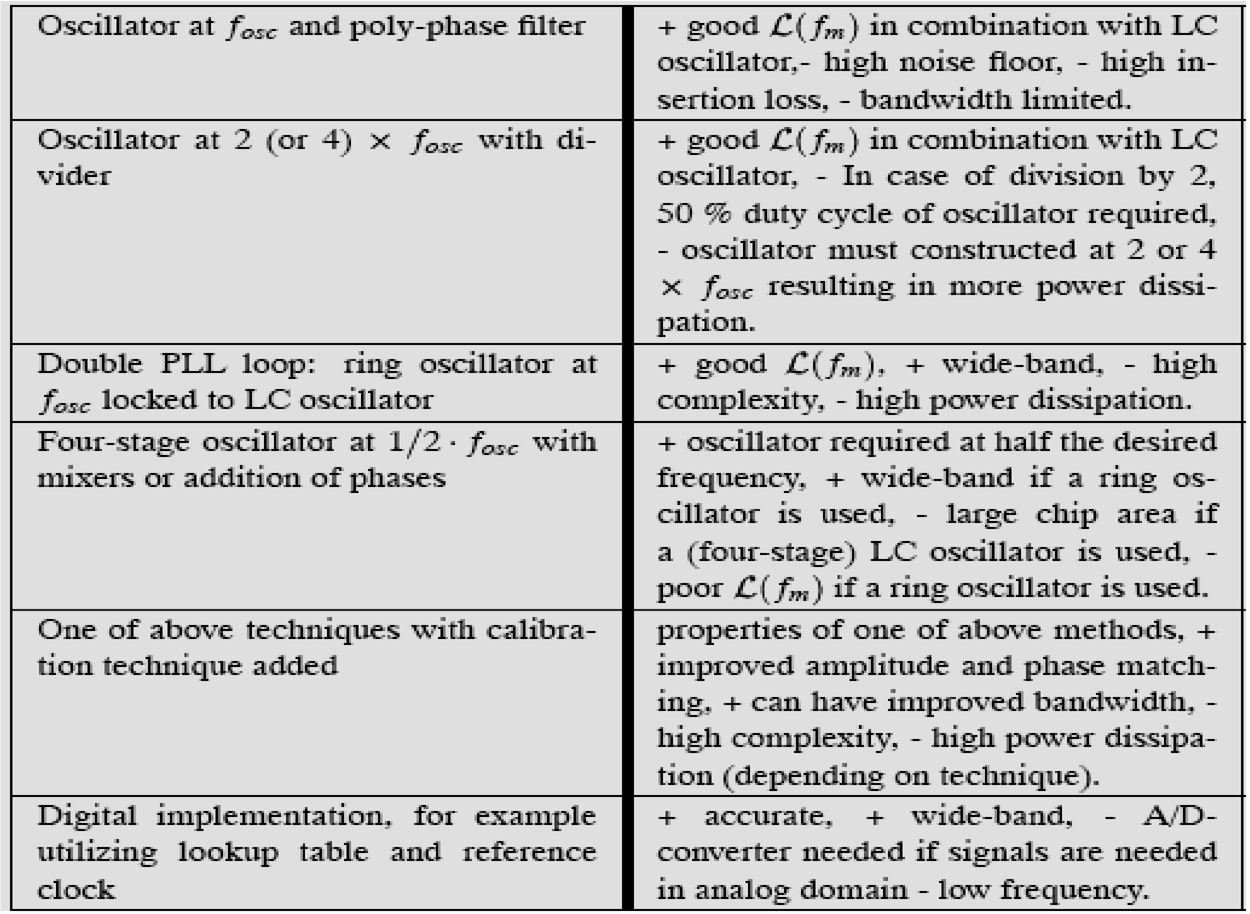
I/Q generation (4)

Even-stage ring oscillators oscillators:



Ring oscillators are relatively very noisy compared to LC oscillators given the same power budget.

Some other I/Q generation methods



Oscillator at f_{osc} and poly-phase filter	+ good $\mathcal{L}(f_m)$ in combination with LC oscillator,- high noise floor, - high insertion loss, - bandwidth limited.
Oscillator at 2 (or 4) × f_{osc} with divider	+ good $\mathcal{L}(f_m)$ in combination with LC oscillator, - In case of division by 2, 50 % duty cycle of oscillator required, - oscillator must constructed at 2 or 4 × f_{osc} resulting in more power dissipation.
Double PLL loop: ring oscillator at f_{osc} locked to LC oscillator	+ good $\mathcal{L}(f_m)$, + wide-band, - high complexity, - high power dissipation.
Four-stage oscillator at $1/2 \cdot f_{osc}$ with mixers or addition of phases	+ oscillator required at half the desired frequency, + wide-band if a ring oscillator is used, - large chip area if a (four-stage) LC oscillator is used, - poor $\mathcal{L}(f_m)$ if a ring oscillator is used.
One of above techniques with calibration technique added	properties of one of above methods, + improved amplitude and phase matching, + can have improved bandwidth, - high complexity, - high power dissipation (depending on technique).
Digital implementation, for example utilizing lookup table and reference clock	+ accurate, + wide-band, - A/D-converter needed if signals are needed in analog domain - low frequency.

Transmitter architectures

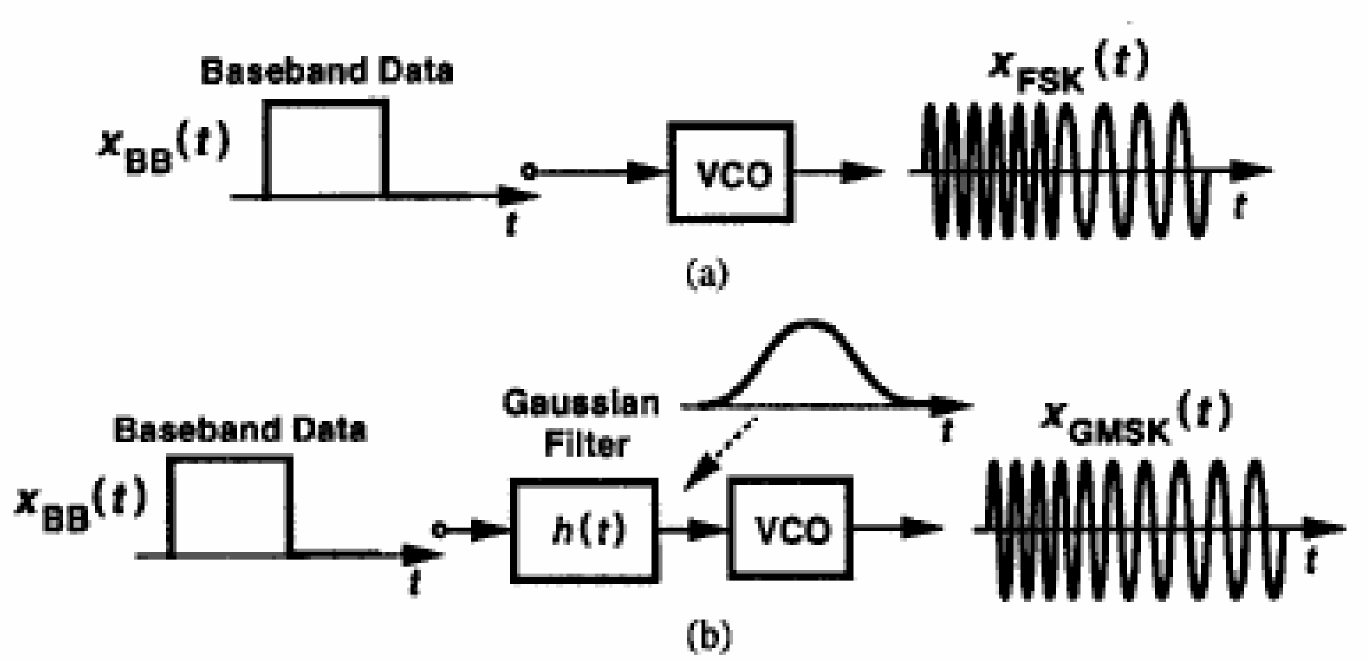
Basic function of a transmitter

What do we want of a transmitter front-end:

A transmitter converts a baseband signal to a higher frequency (i.e. to a specific channel) and amplifies the signal to a specified power level that can drive the antenna.

Baseband
TX
considerations

Constant envelope signals

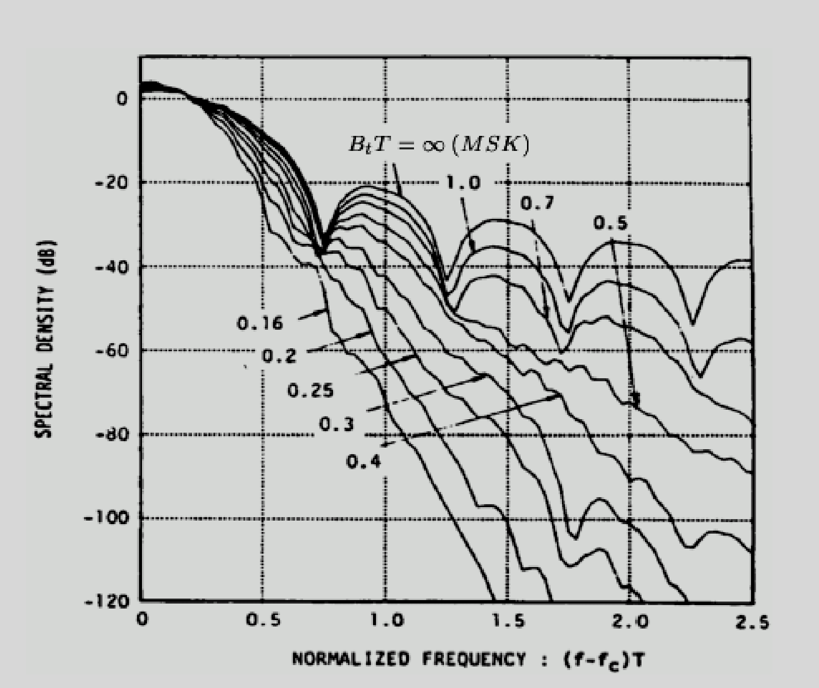


The amplitude of the baseband modulated signal does not vary in time: only info in the phase. This allows the use of a high-efficient switching and non-linear (limiting) power amplifier.

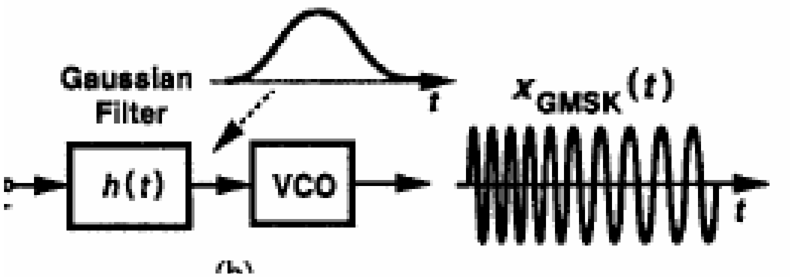
Image: B. Razavi

Pulse shaping can be used to limit spectral content of constant envelope signals

- For example, BPSK occupies a relatively large spectrum.



GMSK (Gaussian minimum shift keying) makes use of a pulse shaping filter to limit the spectral content.



$$h_G(t) = B_t \frac{2\pi}{\ln 2}\, e^{-\frac{2\pi^2 B_t^2}{\ln 2} t^2}$$

3 dB bandwidth of Gaussian LPF filter.

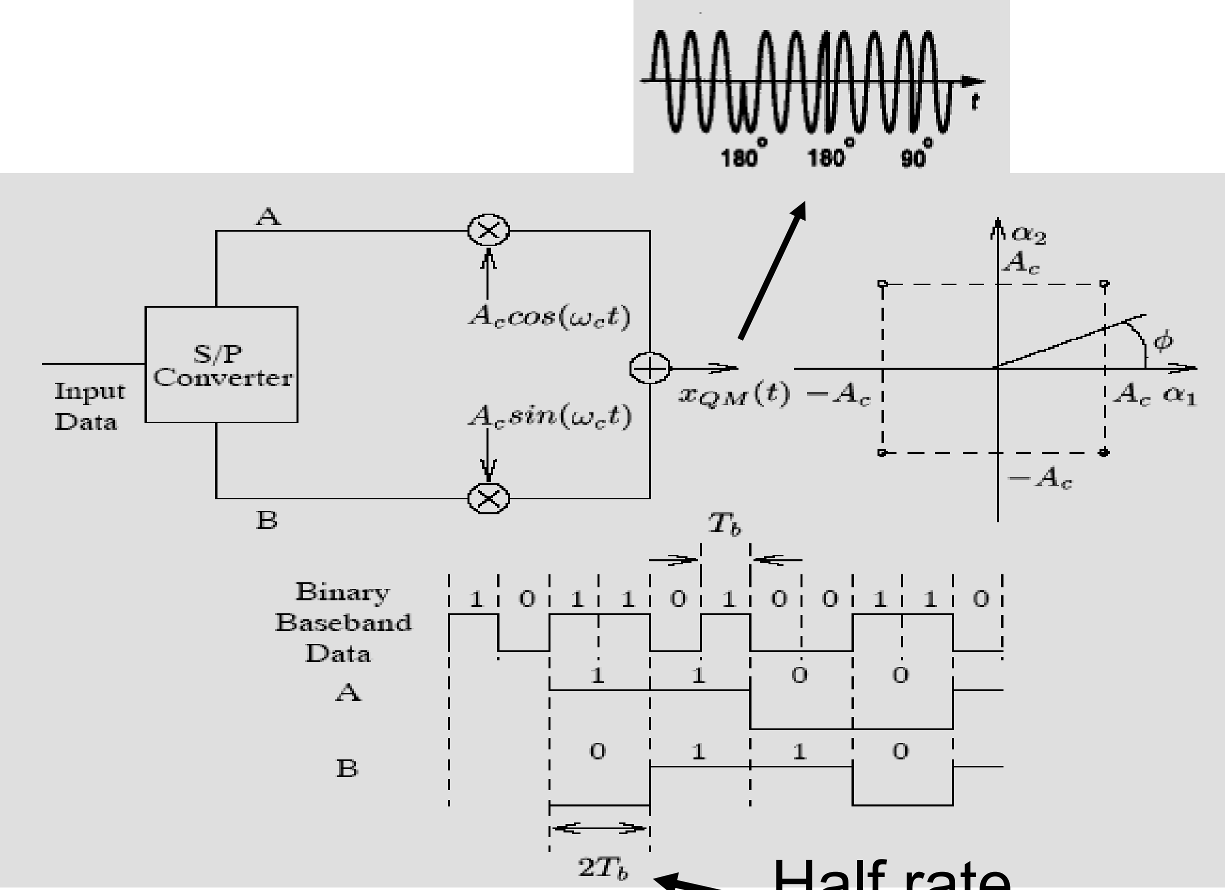
Image: B. Razavi, V. Vidojkovic

Gaussian minimum shift keying widely used

- Examples of standards
  - Digital European Cordless Telephone (DECT)
  - GSM
  - Hyper-lan
  - Frequency hoping part of IEEE 802.11

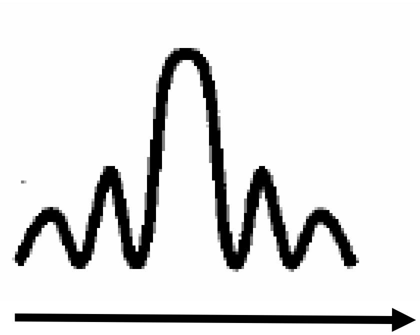
Key advantages is that GSMK (as an example) allows the use of a non-linear, efficient power amplifier while occupying a moderate part of the spectrum. Negative point is that the pulse shaping causes inter-symbol interference (ISI). Using Matched filters in RX and TX helps to minimize ISI.

QPSK modulation



Half rate

QPSK modulation gives, without pulse shaping a lot of spectral content



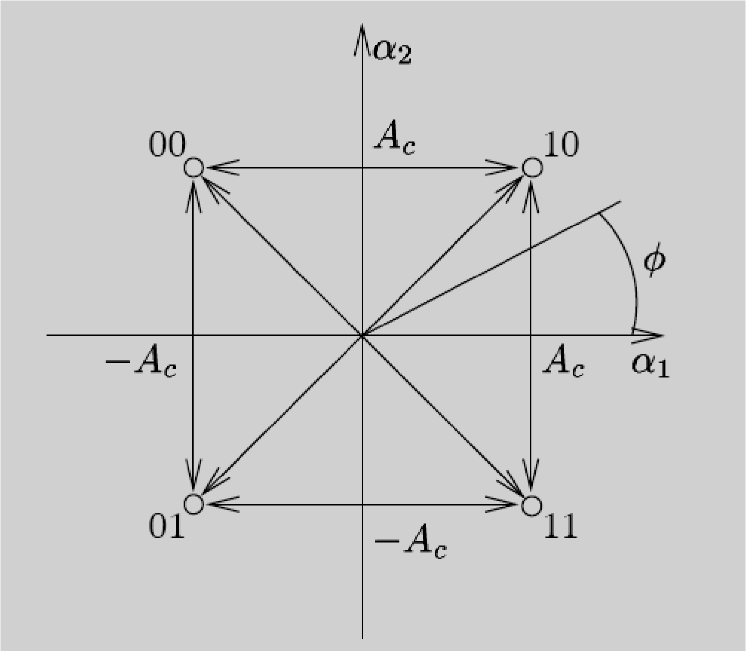
frequency

Image: B. Razavi, V. Vidojkovic

Phase changes in QPSK

$$x_{QPSK}(t) = \sqrt{2}A_c cos(\omega_c t + \frac{k\pi}{4})$$

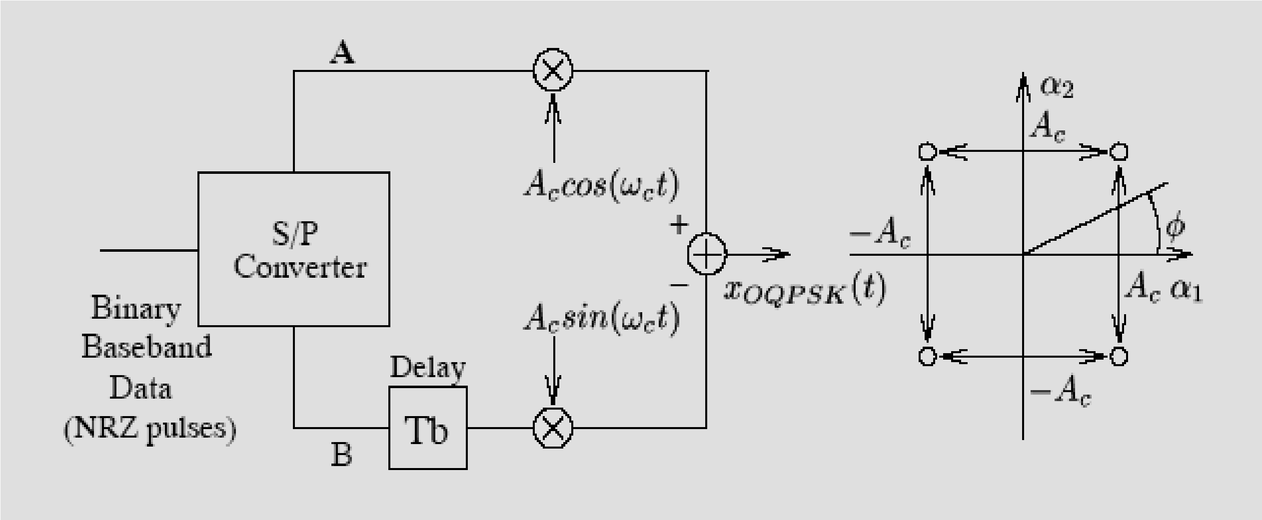
With k=1,3,5 and 7



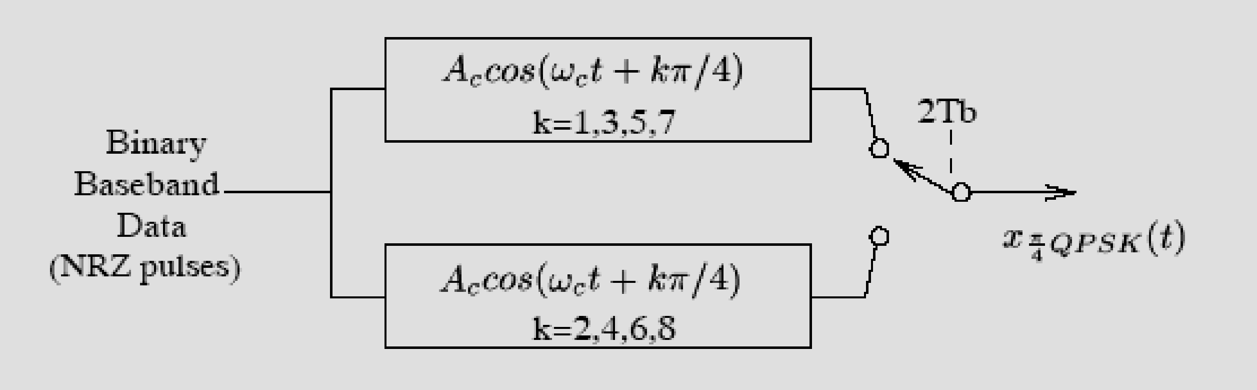
Phase transitions in QPSK signal: worst case *00* to *11* (or vice versa) and *10* to *01 (i.e. π)* . Abrupt phase-changes implies large spectral content.

Image: V. Vidojkovic

Offset QPSK and π/4 QPSK more spectral efficient due to less abrupt phase changes



Offset QPSK, the maximum phase change is π/2.

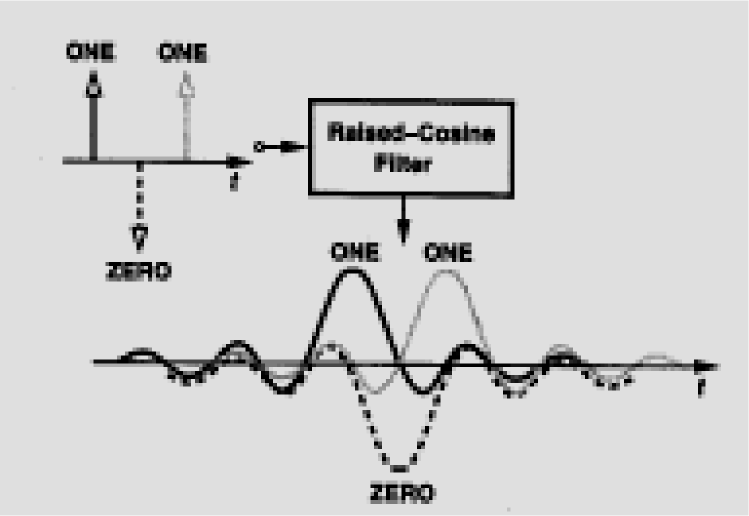


π/4 QPSK, the maximum phase change is 3π/2.

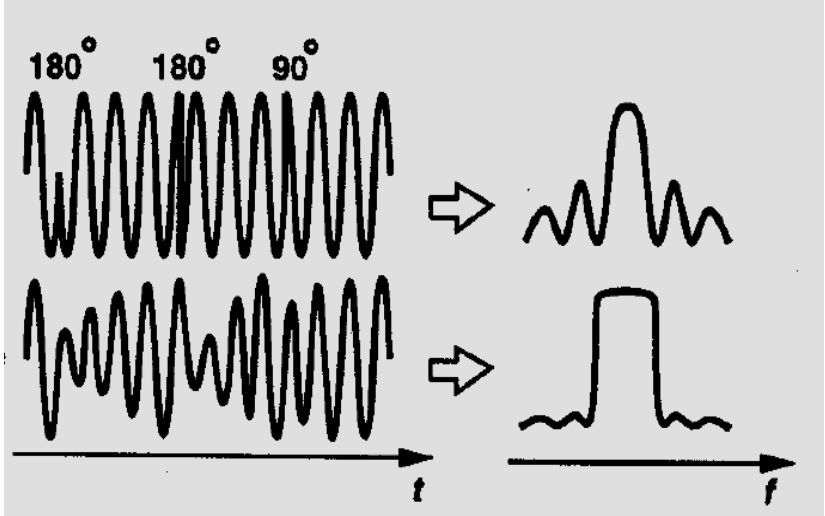
Image: V. Vidojkovic

QPSK with pulse shaping gives a high spectral efficiency at the cost of a non-constant envelope

- Is used in standards like IS-94, IS95 and the spread-spectrum variant of IEEE 802.11



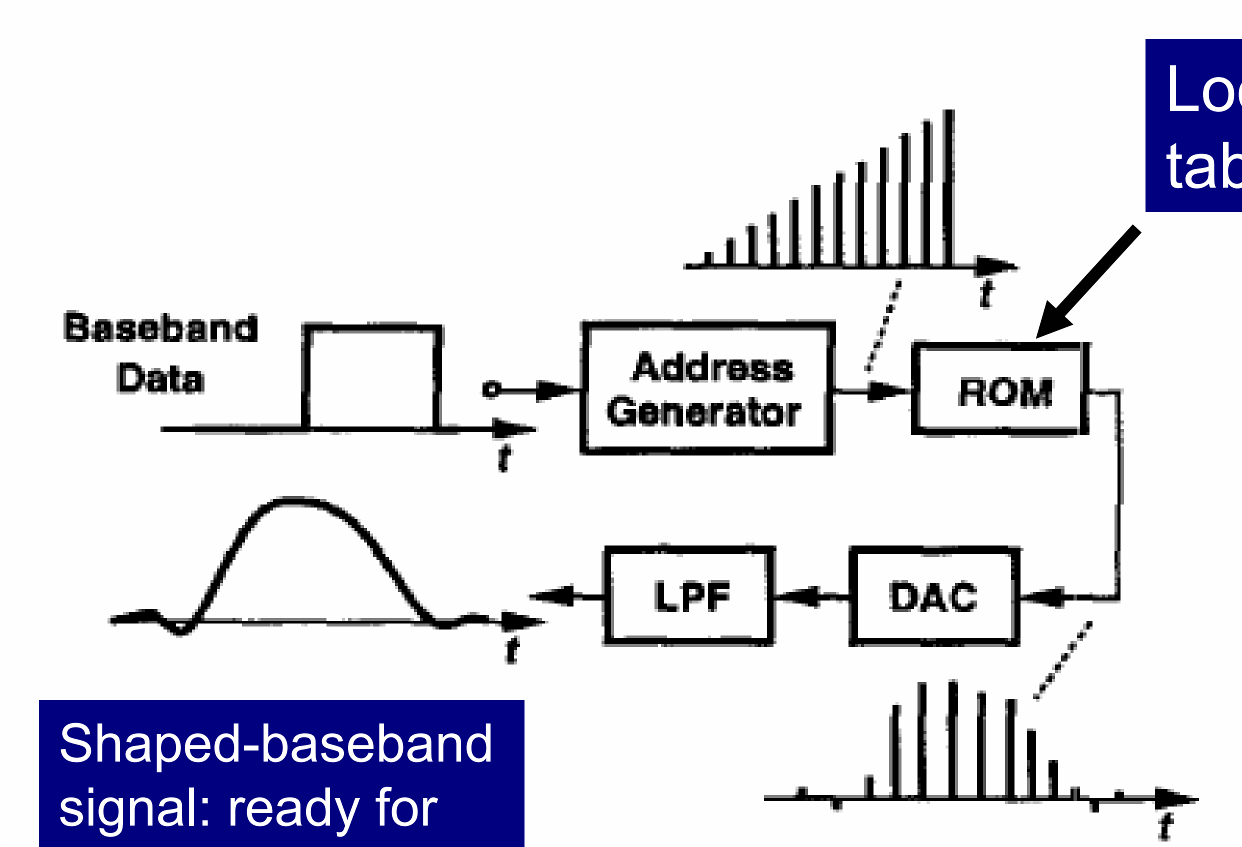
Each bit is represented by a sinc-function.



This yields a block-like spectrum in the frequency domain.

Image: B. Razavi

Example of baseband/RF interface



Look-up table

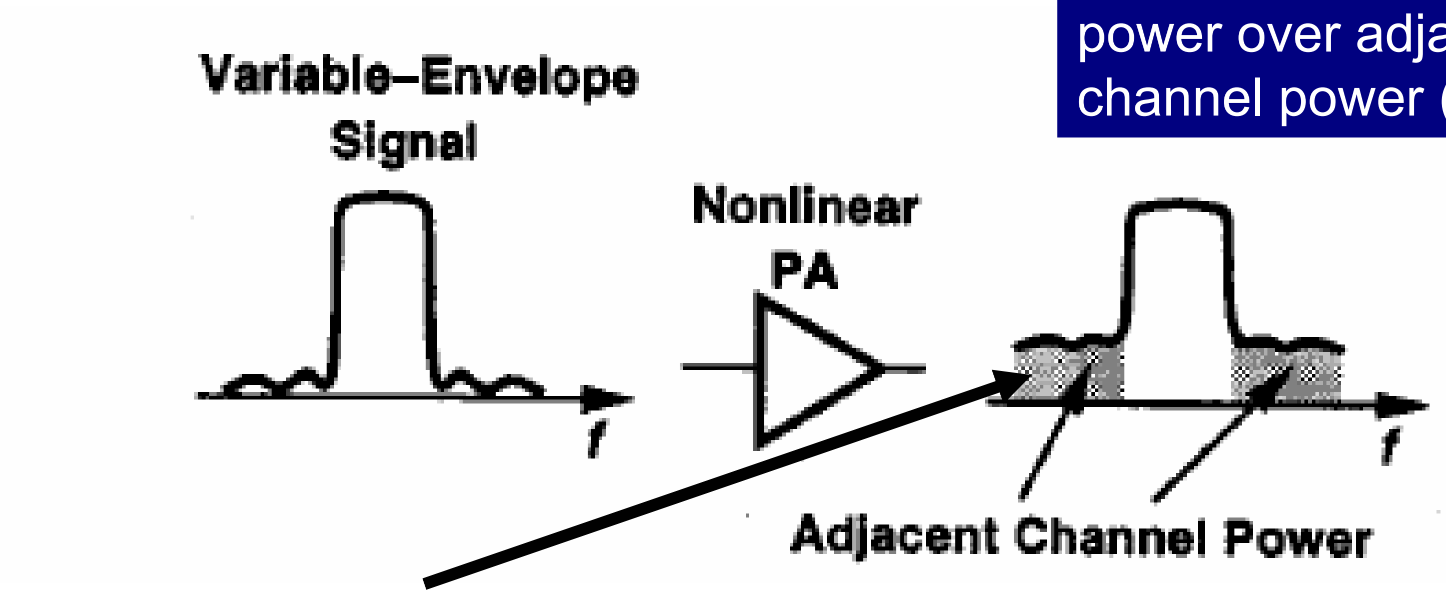
Shaped-baseband signal: ready for up-conversion

Image: B. Razavi

TX specifications

Non-constant envelope modulation & non-linear amplifier gives spectral regrowth

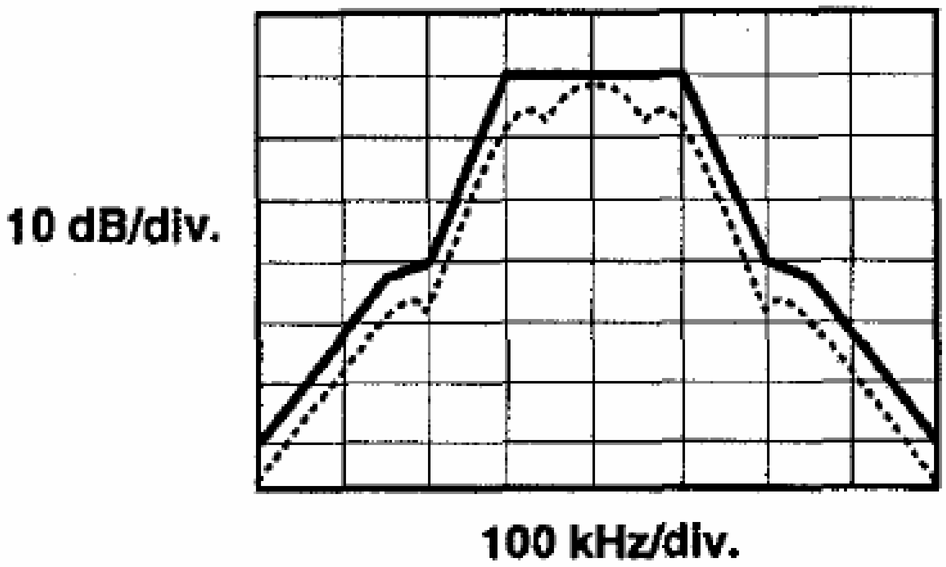
ACPR: channel power over adjacent channel power (dBc).



ACPR: Adjacent channel power ratio, sometimes referred to as ACLR, adjacent channel leakage ratio. If the ACPR is too high: an adjacent channel sees a high interfering signal.

Image: B. Razavi

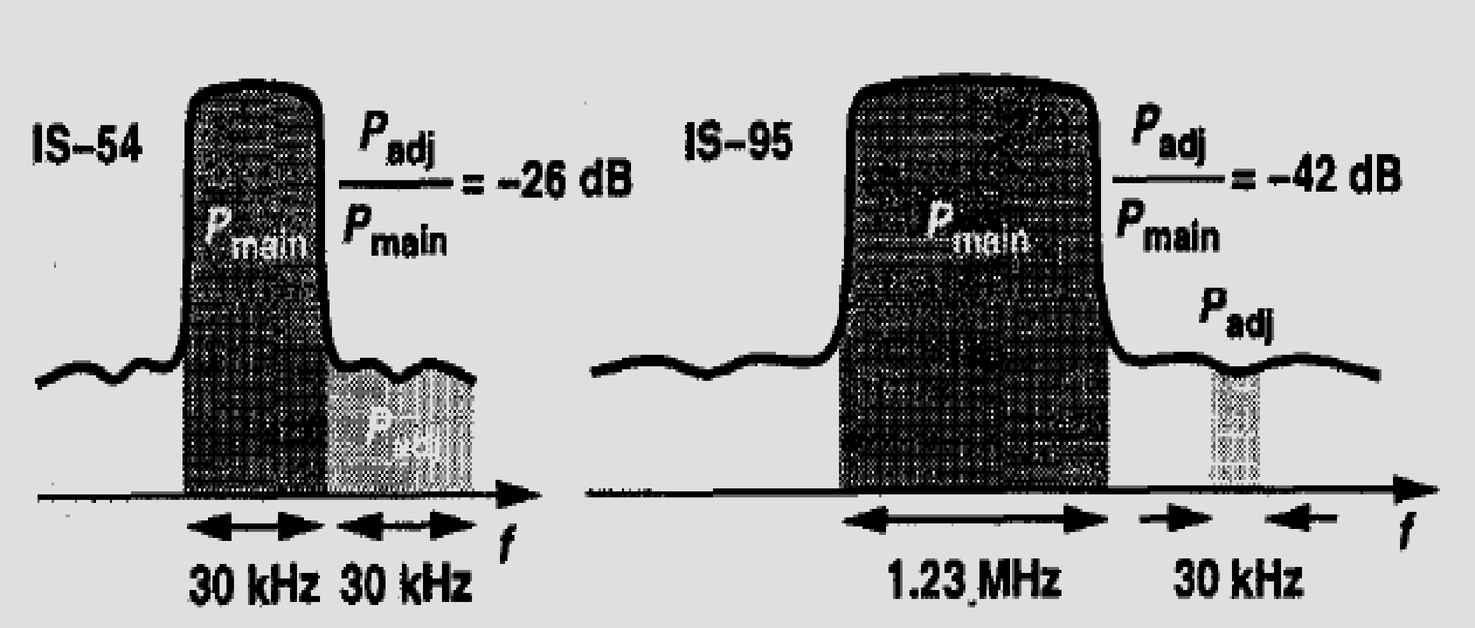
TX spectral emission masks



TX spectral content is specified by TX emission masks. This example shows an emission mask for GSM.

Image: B. Razavi

In standards with non-constant envelope modulation, ACPR is specified



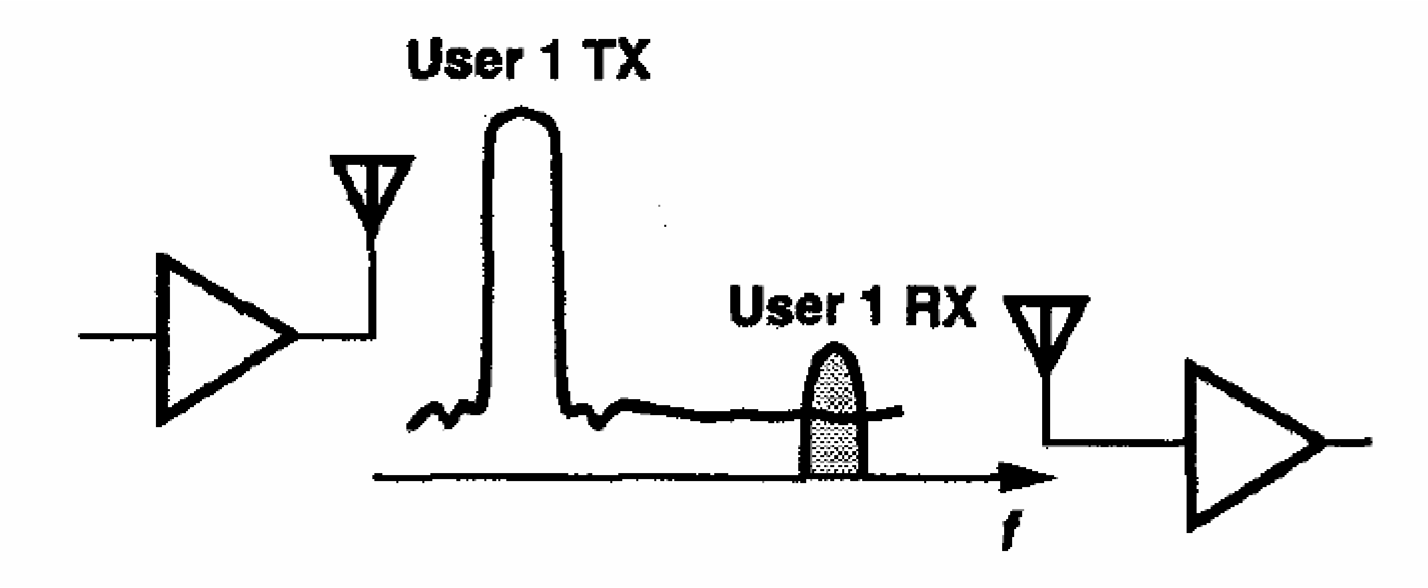
IS-94 standard (USA)

IS-95 standard (USA)

The ACPR spec. enforces sufficient linearity in up-conversion mixers and power amplifiers of the TX.

Image: B. Razavi

Transmitted noise

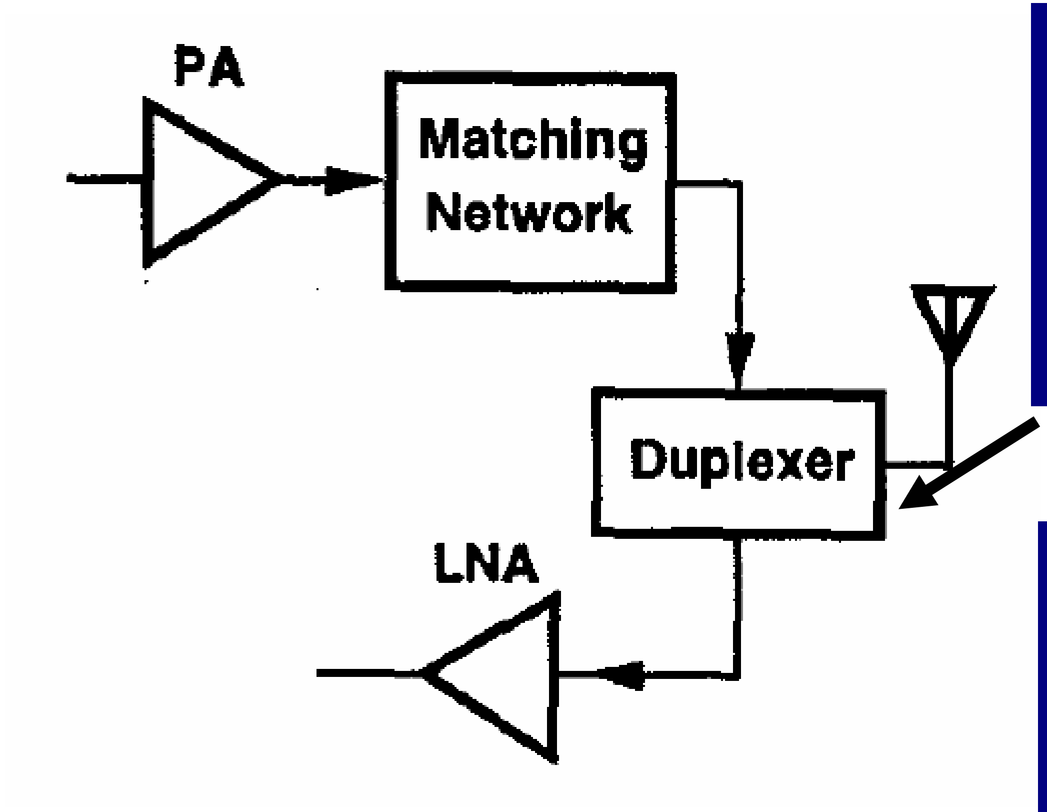


The transmitter noise in the RX band must be very low for a standard like GSM: if two users are near each other the noise in the RX band may corrupt the desired signal.

Image: B. Razavi

General RF TX issues

PA-antenna interface



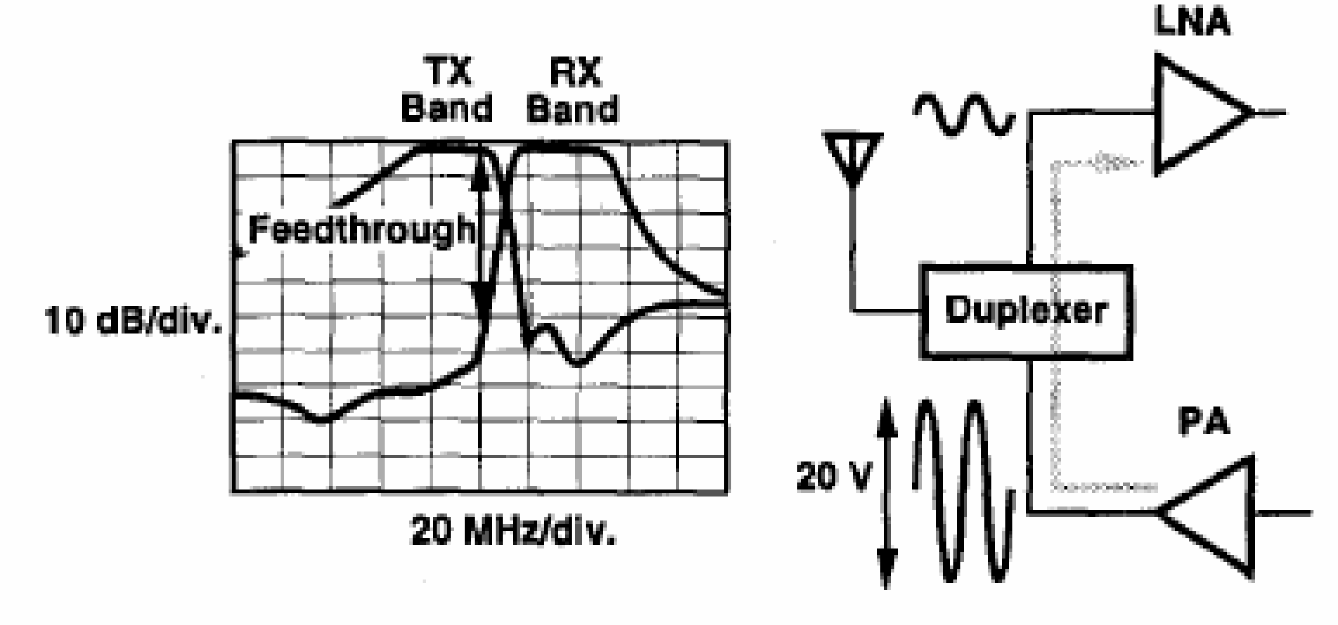
Separates the RX frequency and the TX frequency in case of FDD.

The duplexer is replaced by an RF switch in case of TDD

Image: B. Razavi

Duplexer only offers finite isolation

Feed-through from TX to RX path

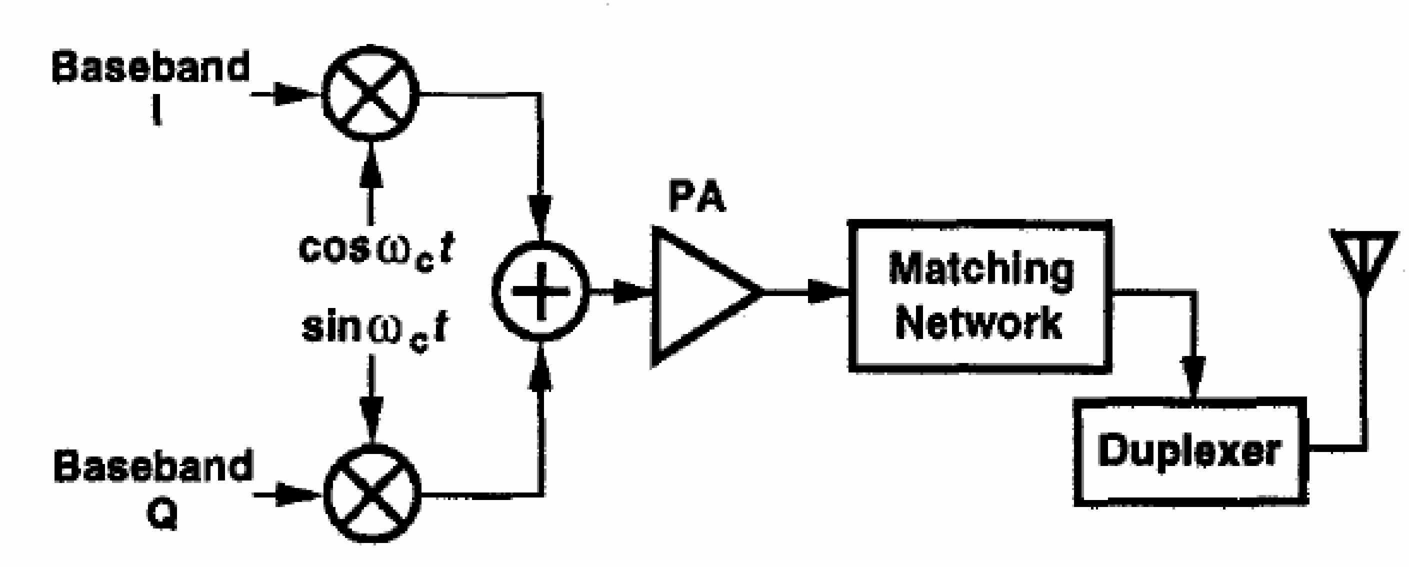


Duplexer may have 2-3 dB insertion loss. Solution (used in GSM) for feed-through is to use non-overlapping time slots for RX and TX.

Image: B. Razavi

Direct-conversion transmitters

Direct-conversion TX

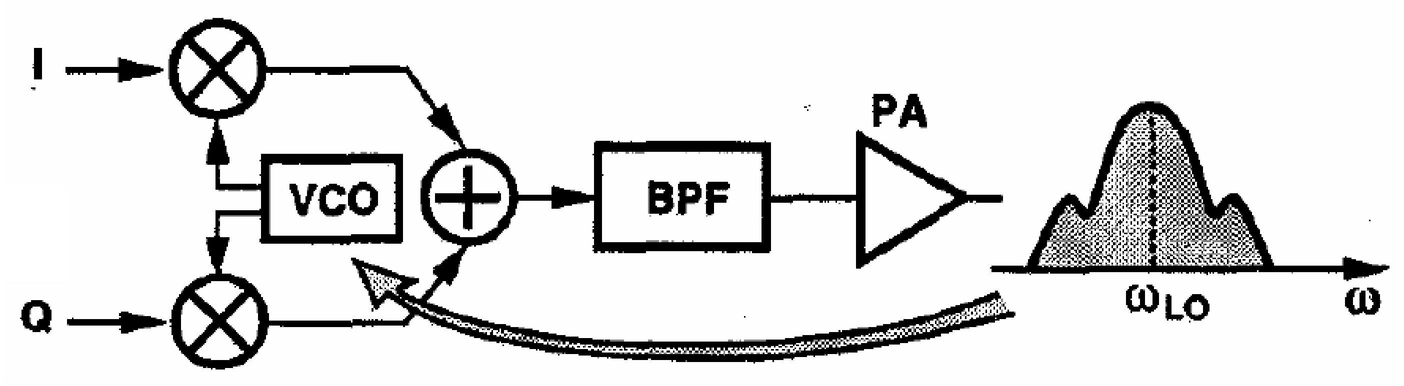


Simple architecture. LO frequency is the same as the output frequency, and up-conversion and quadrature modulation are combined in the same circuitry.

Image: B. Razavi

Major disadvantage of direct-conversion TX

Output signal of PA modulates local oscillator: LO pulling

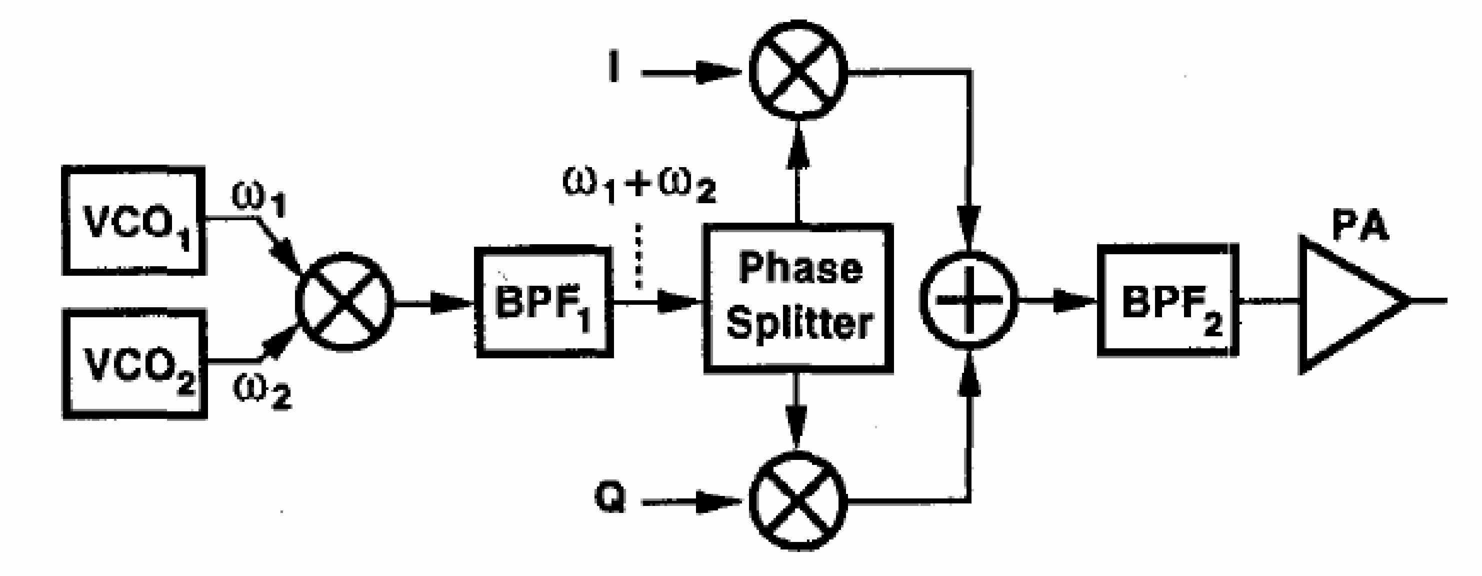


Depending on the level of the injected signal into the oscillator the oscillator may be modulated in a noisy fashion or even “pulled” away from its intended frequency.

Image: B. Razavi

Direct-conversion transmitters with offset LO

Direct-conversion with offset LO



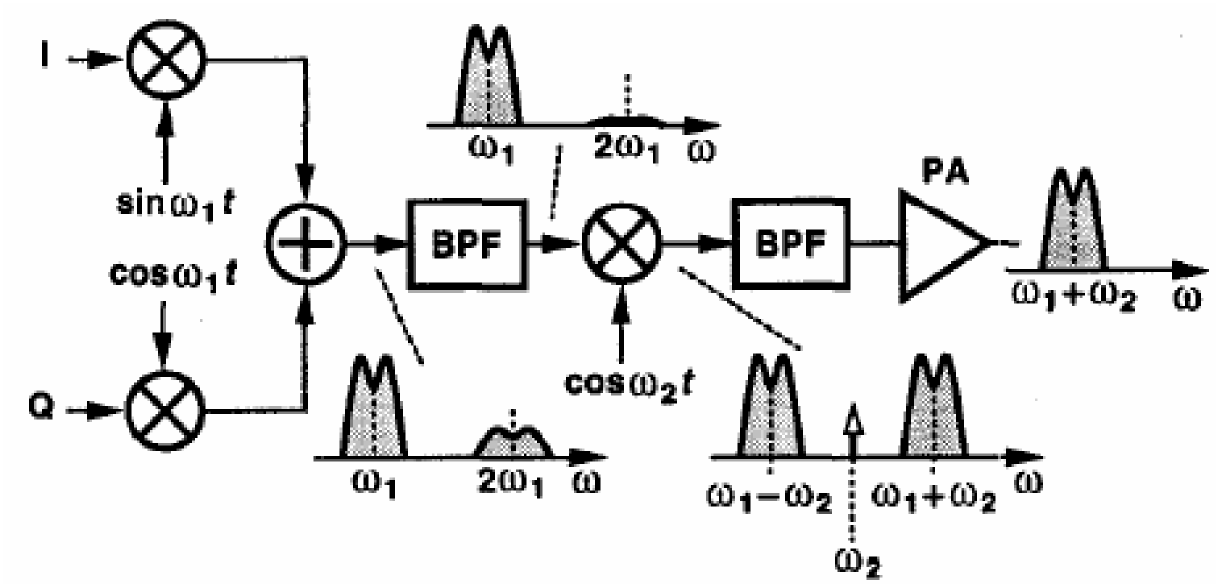
LO frequencies unequal to output frequency, hence pulling problem is alleviated. BPF must be good enough to suppress all unwanted mixing products sufficiently.

Image: B. Razavi

Two-step transmitter architecture

Two-step transmitter architecture

- Two up-conversions to remove LO pulling problem



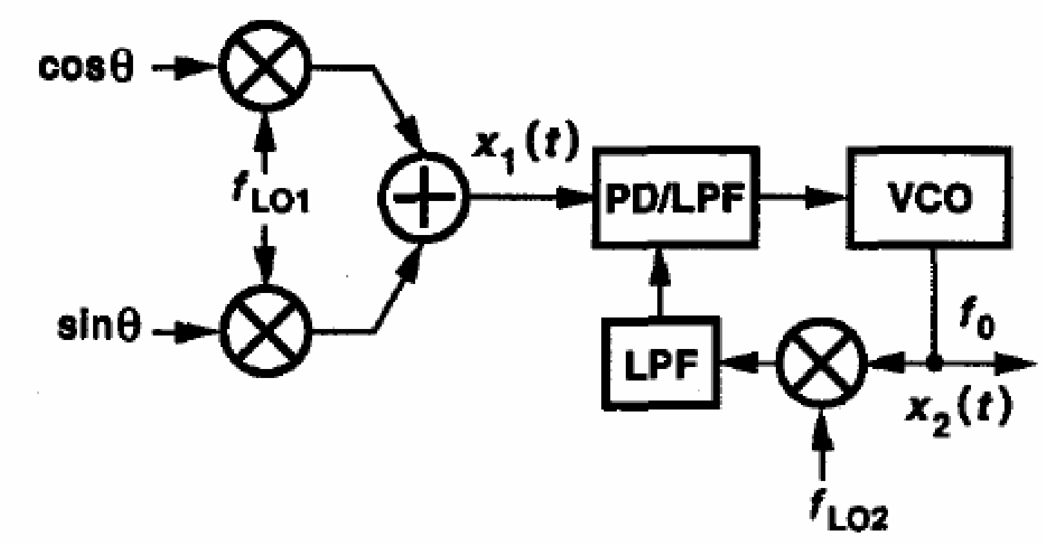
Bandpass filters are difficult to make on-chip and may require 50-60 dB suppression of unwanted conversion product.

Image: B. Razavi

Offset-PLL transmitter architecture

Offset PLL architectures

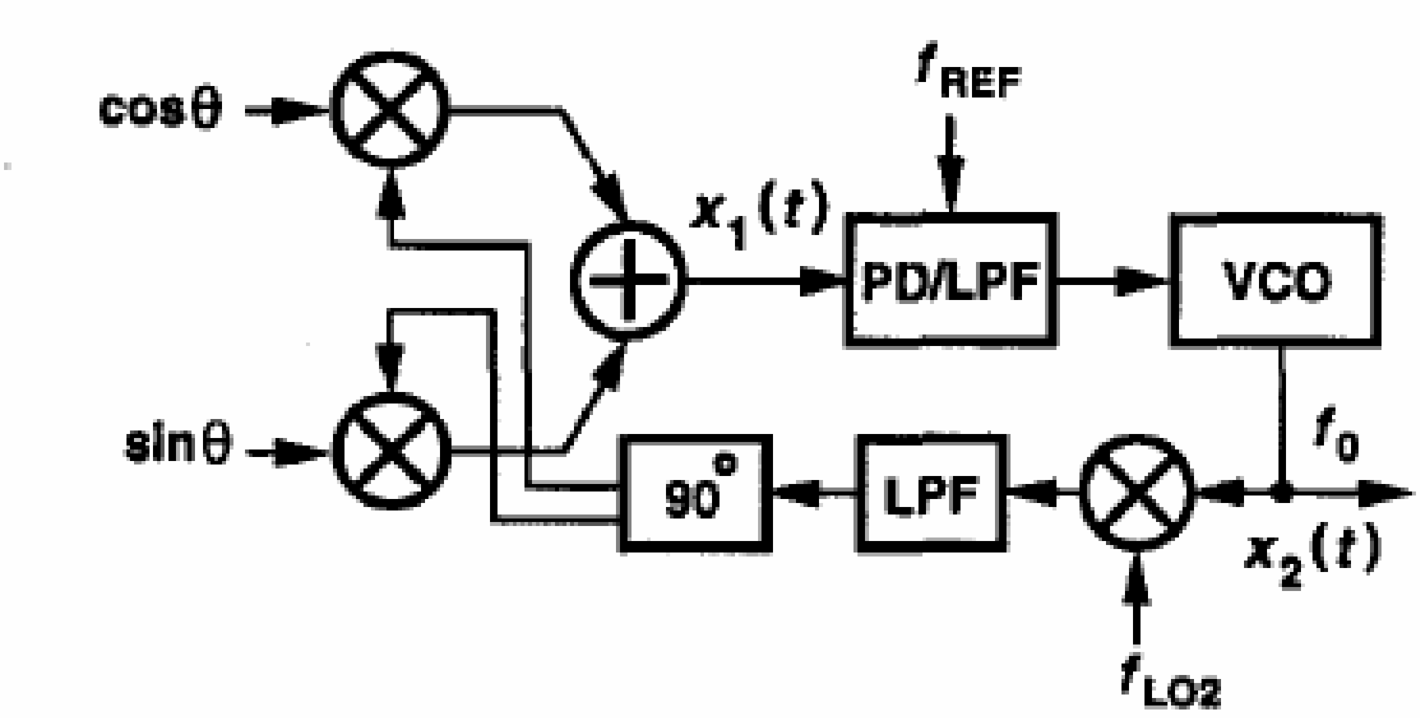
Only for constant envelope systems



Second LO, $f_{LO2,}$ reduces input frequency of phase detector: $f_o = f_{LO1} + f_{LO2}$. The architecture is relatively complex but offers excellent out-of-band noise performance.

Image: B. Razavi

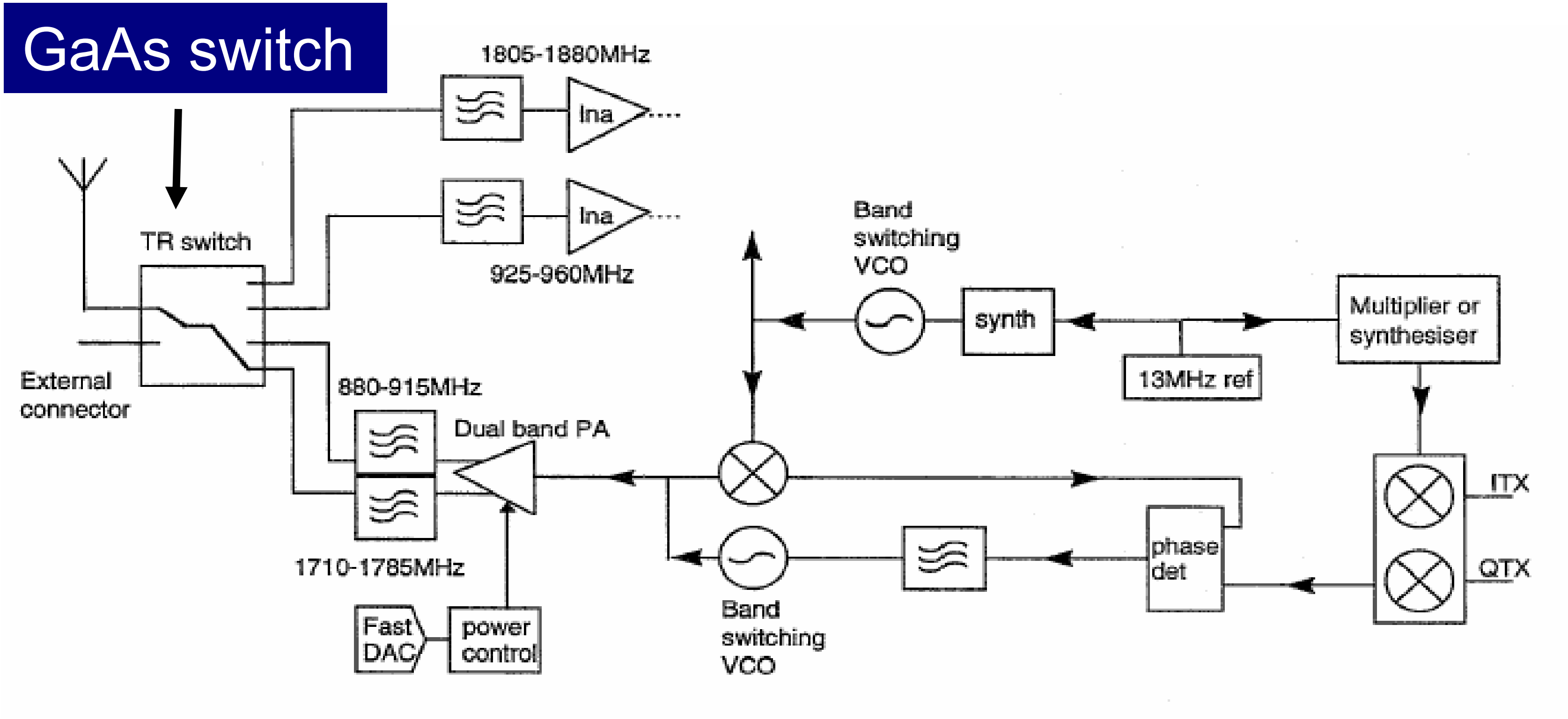
Offset PLL architecture can be combined with quadrature up-conversion



The phase lock loop uses a fixed reference frequency f_{ref}, in order to have a accurate translation of $X_1(t)$ to $X_2(t)$.

Image: B. Razavi

Example of dual band PLL offset architecture



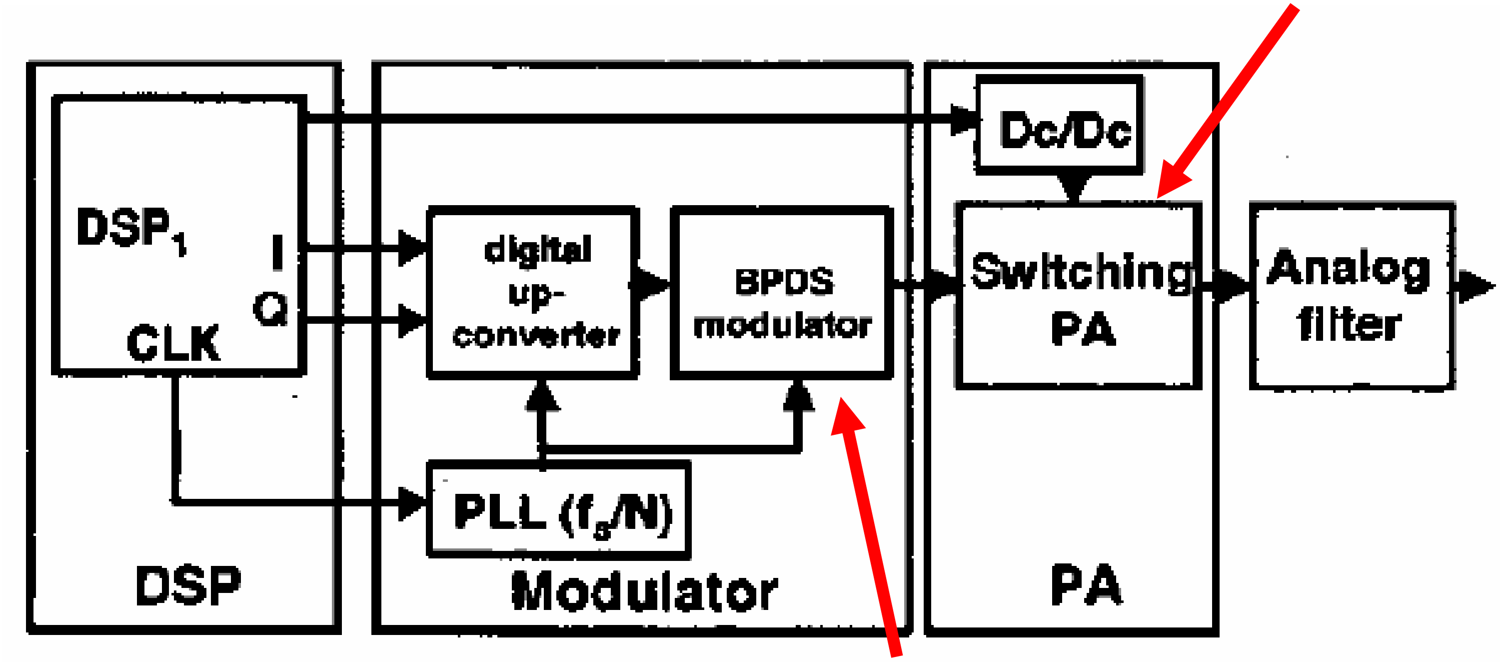
GaAs switch

Dual-band PA removes the need for a bulky transmit duplex filter.

Source: M.H. Norris

Digital transmitter concept example

Digital transmitter concept

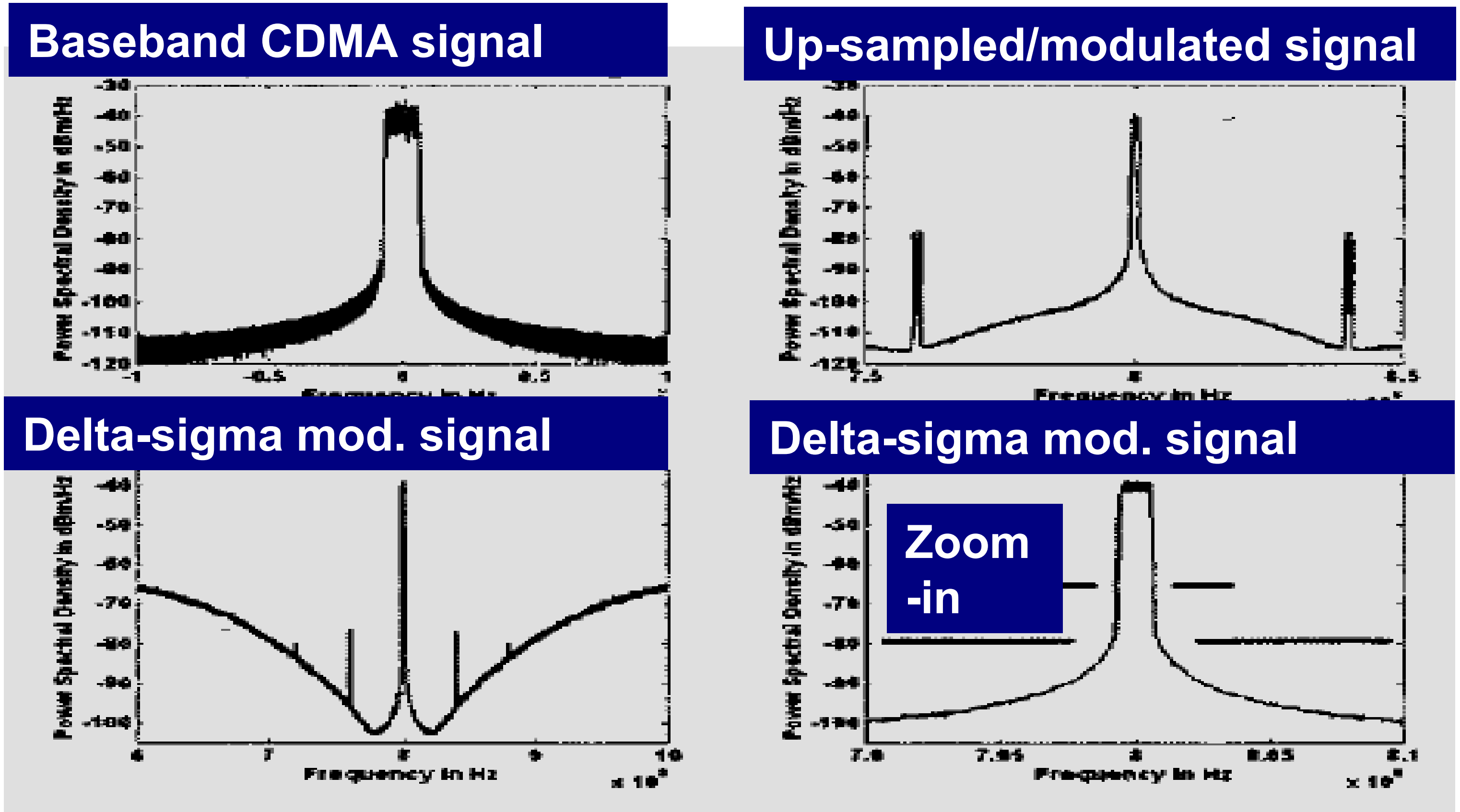


Envelope signal

Band pass delta sigma (BPDS) modulator

Source:Rode, Hinrich,Asbeck

Simulated spectra of digital transmitter concept


Baseband CDMA signal

Up-sampled/modulated signal

Delta-sigma mod. signal

Delta-sigma mod. signal

Zoom -in

Source:Rode, Hinrich,Asbeck