Wireless Transceiver Electronics (WTE)

Wireless Receiver Architectures

Course # 4/9

EWI course 121150

Previous and next lecture

Last course: Wireless Transmitter Architectures

Choice of TX architecture mainly defined by:

- PA efficiency => constant envelope desired (only FM or PM)
- Spectral efficiency => non-constant envelope signals
- Spectral purity (spectral mask, ACPR requirements)

Key functions: PA, mixer, quadrature generation

Transmitter Architectures:

- Direct upconversion (but: LO-pulling problem)
- Offset-upconversion or Two-step architecture to avoid it
- Phase modulation via Offset-PLL modulators: compact, clean spectrum

Next course: Oscillators

This course: Wireless Receiver architectures

Contents Receiver Transceivers lecture

- Introduction: which functions and why?
  - filtering
  - downconversion
  - image rejection
- Image Reject Filter Architectures
  - Super-heterodyne
  - Up-conversion receiver
- Image-reject architectures (image cancelling)
  - Direct-Conversion receivers
  - Low-IF receivers
  - Digital-IF receiver example

Examples of derivative receiver architecture

Introduction:

What functions

& why?

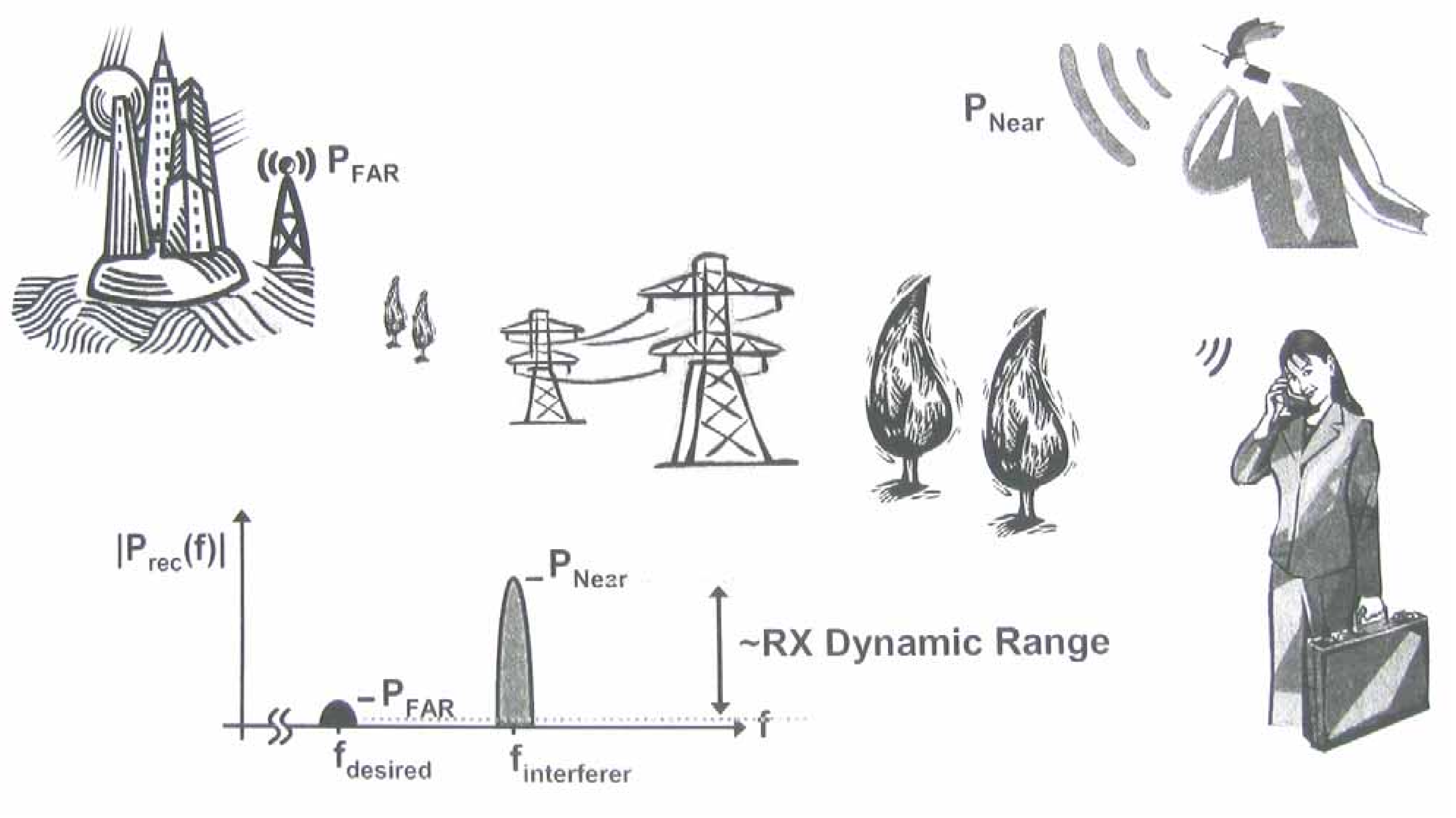
Basic function of a receiver front-end

What do we want of a receiver front-end:

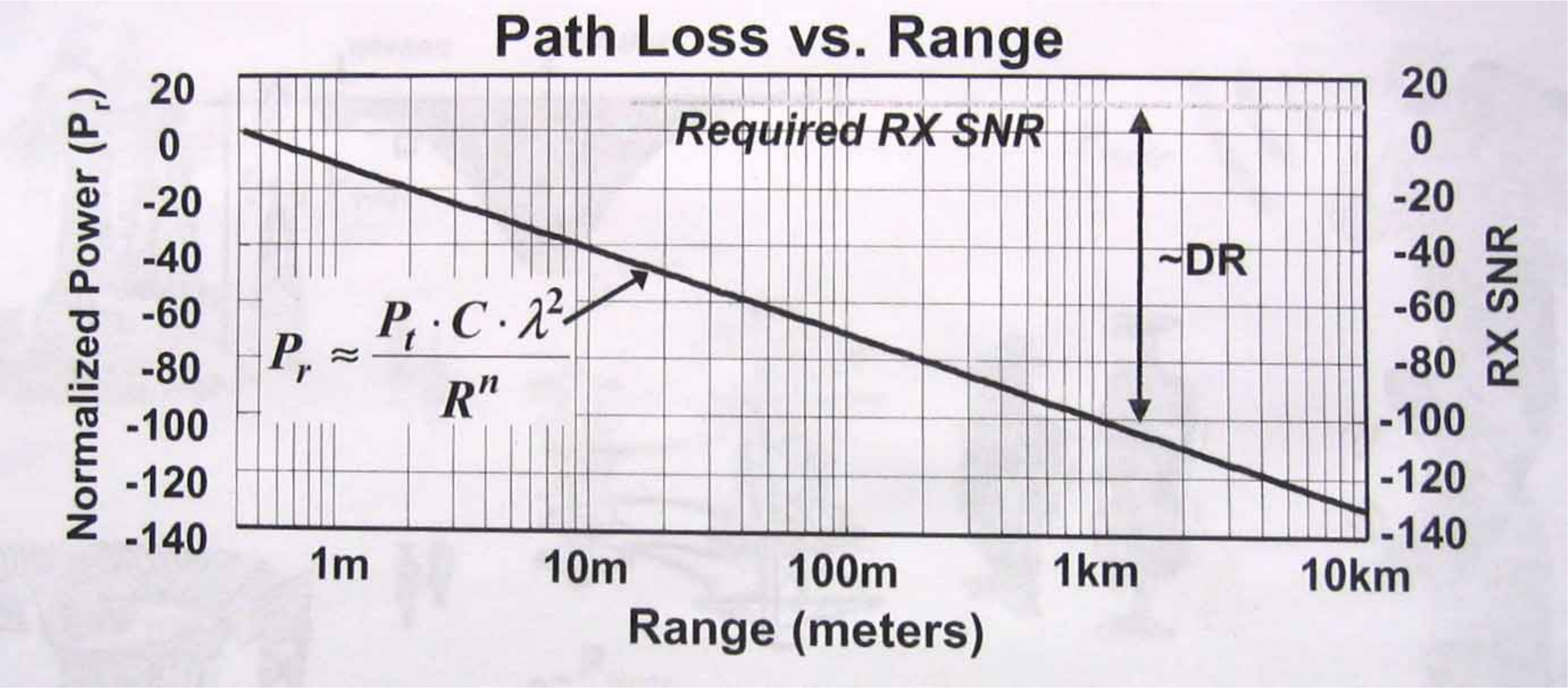
Select and demodulate a (small) desired channel or signal among many interferers: we need ***selectivity*** (analog or digital filter) and usually also ***gain***

Often sufficiently high-Q filters and ADC+DSP not feasible at RF => ***frequency down-conversion***

Near/far problem => RX Dynamic Range



Longer distance => larger Dynamic Range (DR)



Path loss at least with n=2, typically 3-4 (multi-path)

Difference between strongest and weakest signal increases with maximum distance => more tough Dynamic Range requirements

(e.g. Bluetooth or DECT lower DR then GSM)

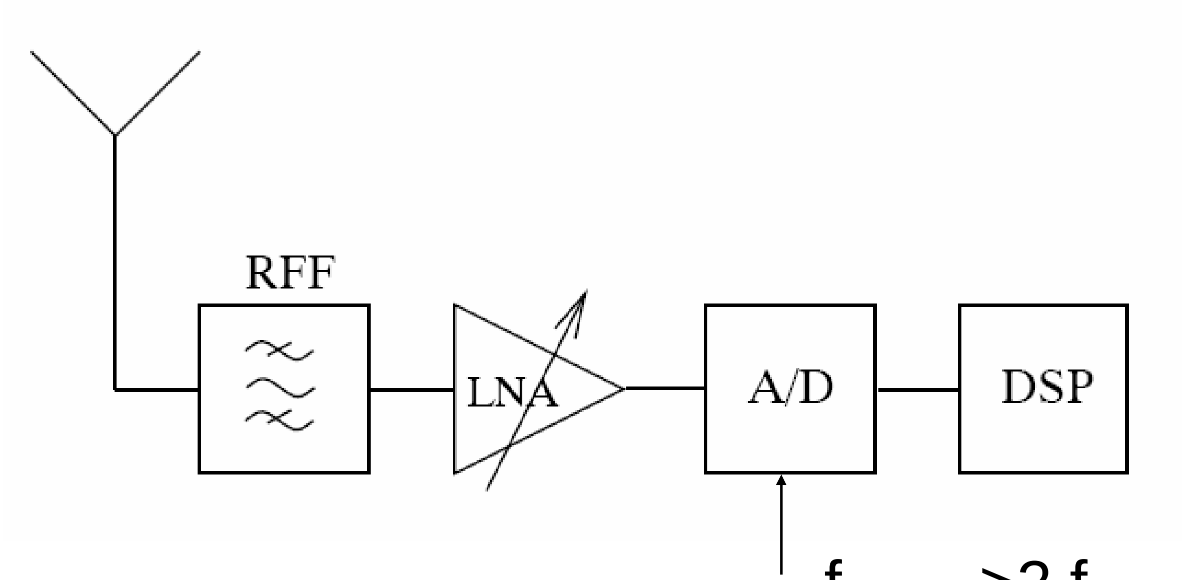
Sampling

based

Receivers

“Full Nyquist” A/D conversion after RF sampling

Digitization almost directly at the antenna



$f_{sample} > 2\ f_{RF,max}$

(satisfy Nyquist criterium)

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

Full Nyquist ADC Power Estimation Example

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 (which is not yet feasible)
- Good state-of-the-art ADC (2005): 1fJ / conversion

$$P = E_{conv} f_{sample} 2^{\#bits} \approx 65\, Watt$$

(2-3 orders of magnitude to high for battery system)

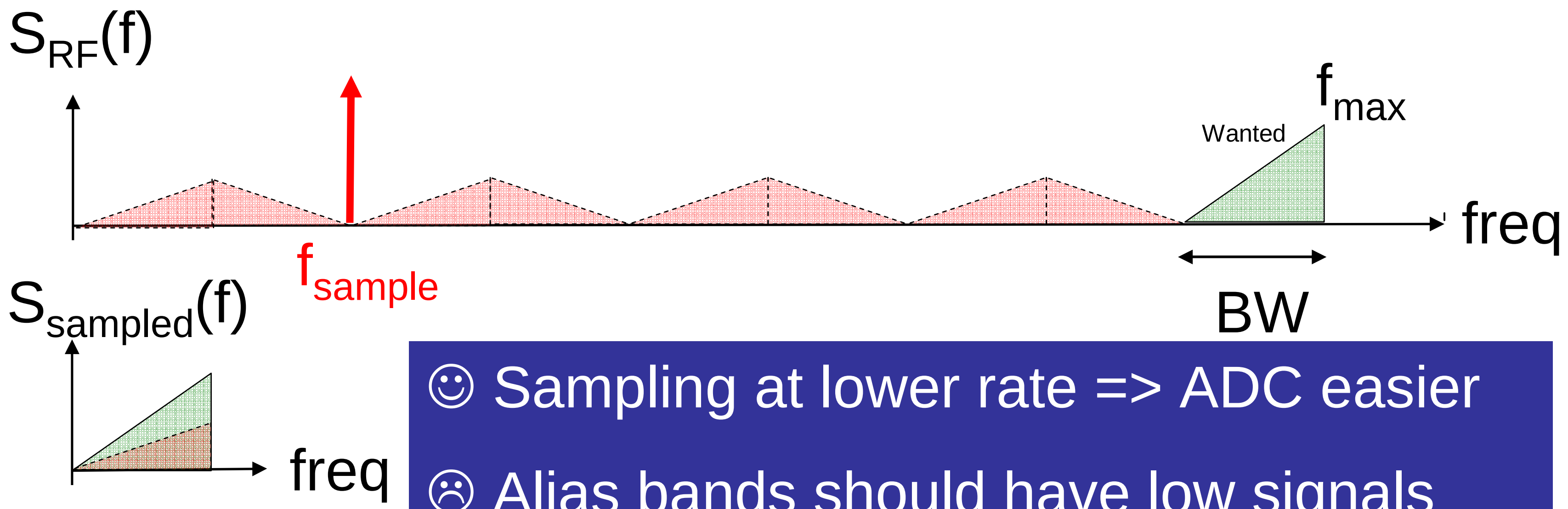
When RF sampling becomes cost-effective it will be the most flexible “software-defined” receiver implementation

Subsampling ADC ($f_{sample} < 2\ f_{Nyquist}$)

Exploit narrowband nature of RF signal:

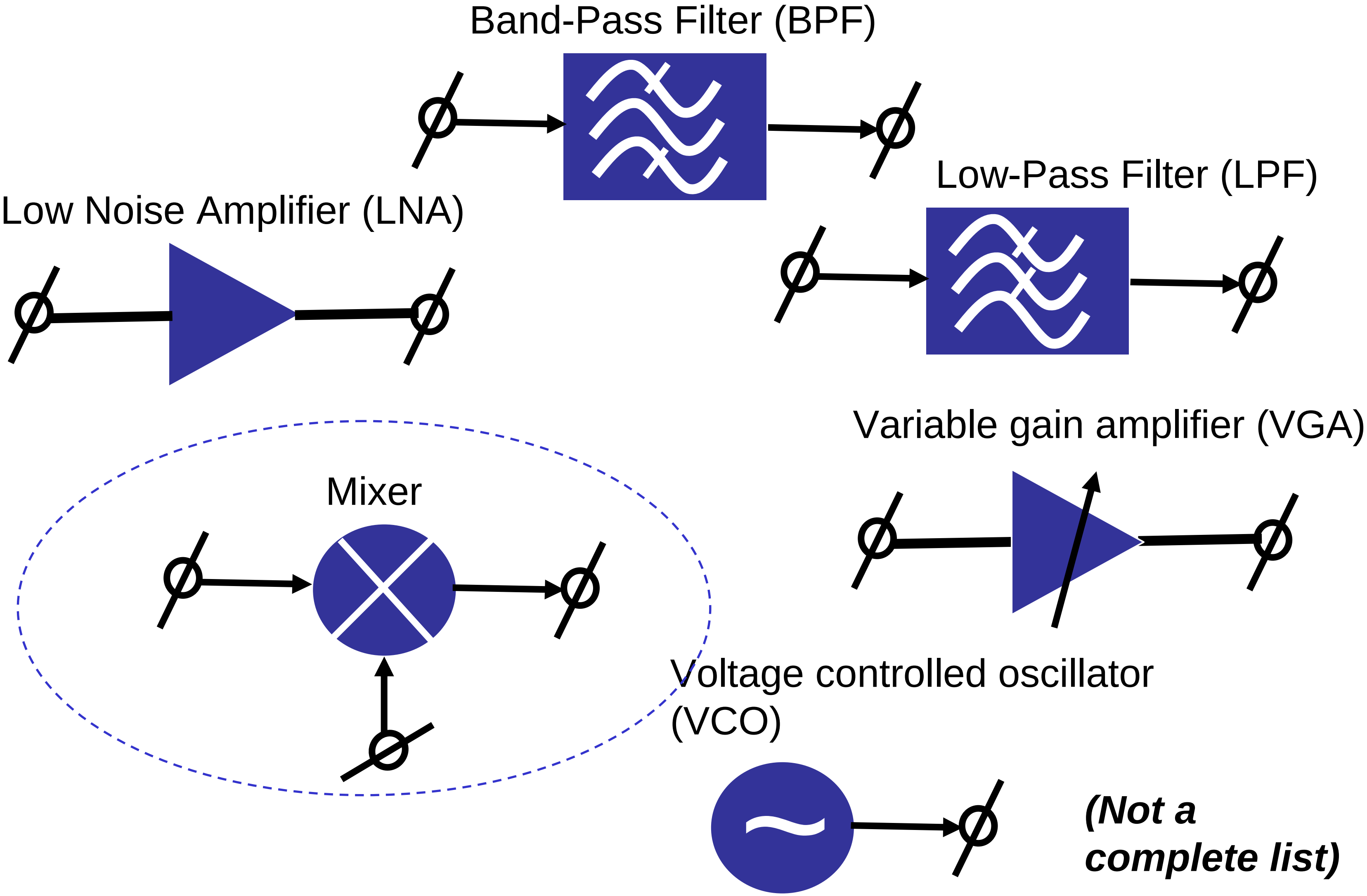
(BW << carrier frequency)

If $f_{sample} > 2$ BW, then modulation info is still captured!



- ☺ Sampling at lower rate => ADC easier
- ☹ Alias bands should have low signals
- ☹ Noise from alias bands (“Noise folding”)

Look for solution using other building blocks



Band-Pass Filter (BPF)

Low-Pass Filter (LPF)

Low Noise Amplifier (LNA)

Variable gain amplifier (VGA)

Mixer

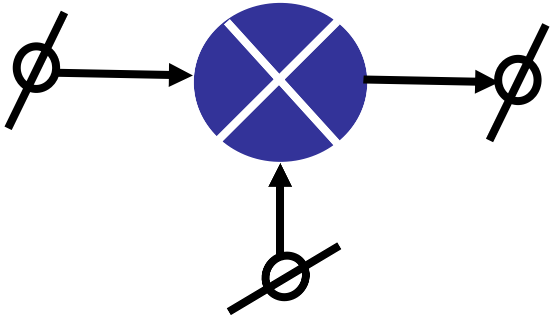
Voltage controlled oscillator (VCO)

(Not a complete list)

Frequency conversion: mixing frequencies

Radio frequency (RF) input

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



Intermediate frequency (IF) output

$$IF_{out} =$$

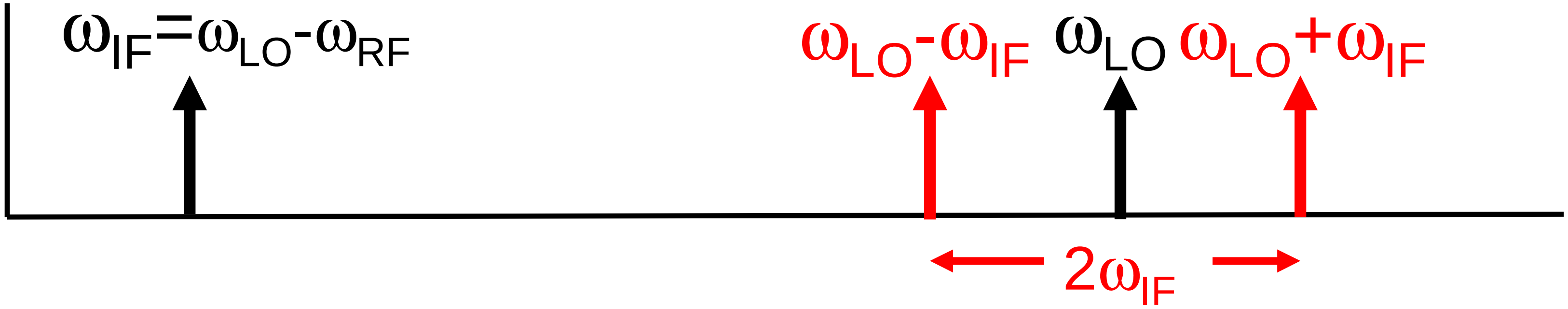
$$\cos((\omega_{RF} - \omega_{LO})t) +$$

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

Local oscillator (LO)

(auxiliary) input

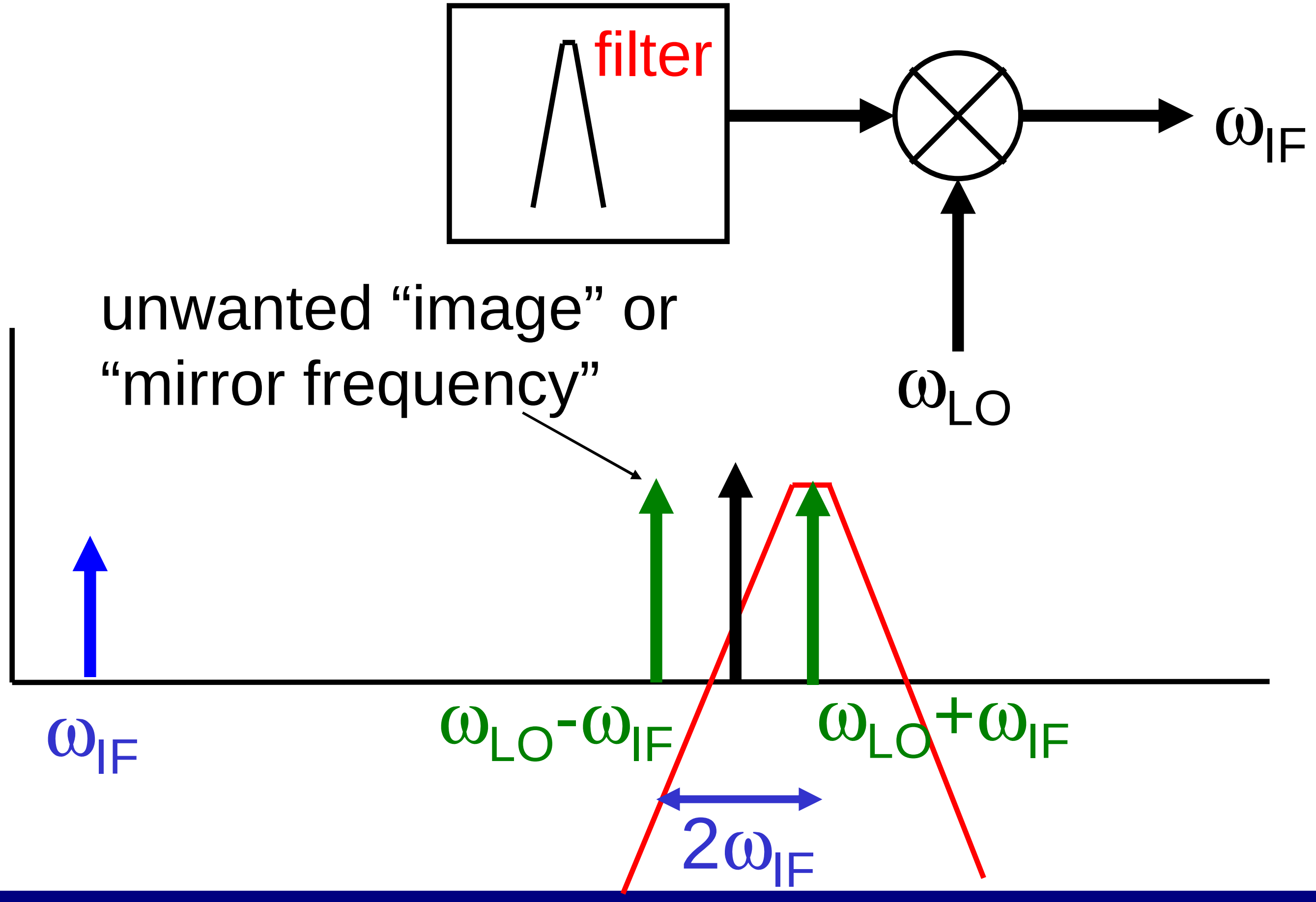
$$LO_{in} = 2\cos(\omega_{LO} t)$$



“Image problem”: two RF frequencies render identical IF-frequency!

Only one is wanted (upper or lower sideband); the other is called “image”

Solution: image rejection bandpass pre-filter



Pre-select upperband via filter (lower also possible)

But: filter has limit roll-off (e.g. 6dB/octave/order)

Example: Image Reject filter requirement

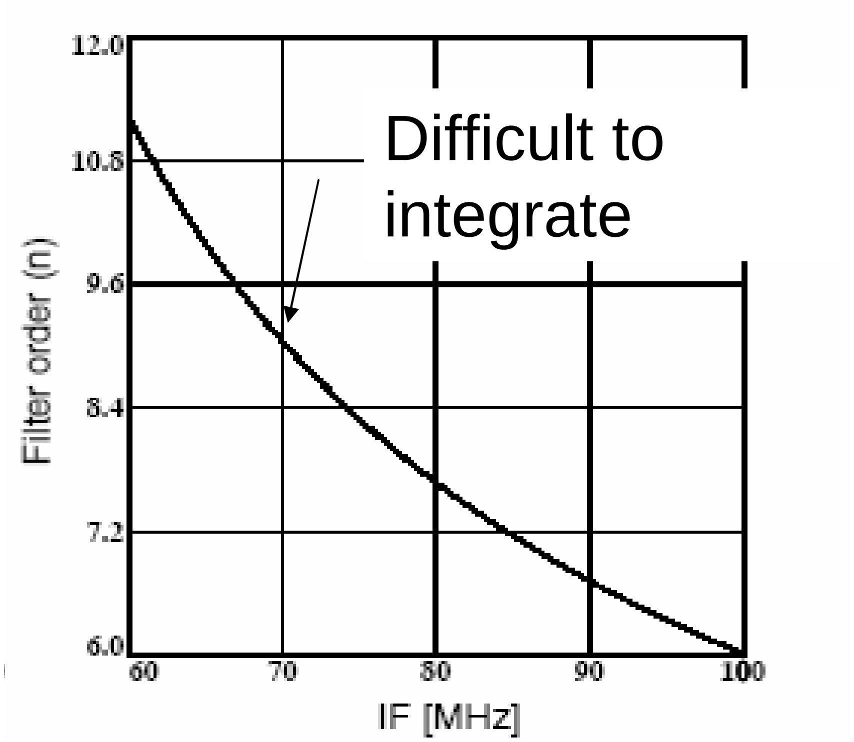
f_{image} and the filter order depends on choice of IF frequency

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

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

Example nth order LC Band Pass Filter design: use e.g. free filter design Software “Elsie”

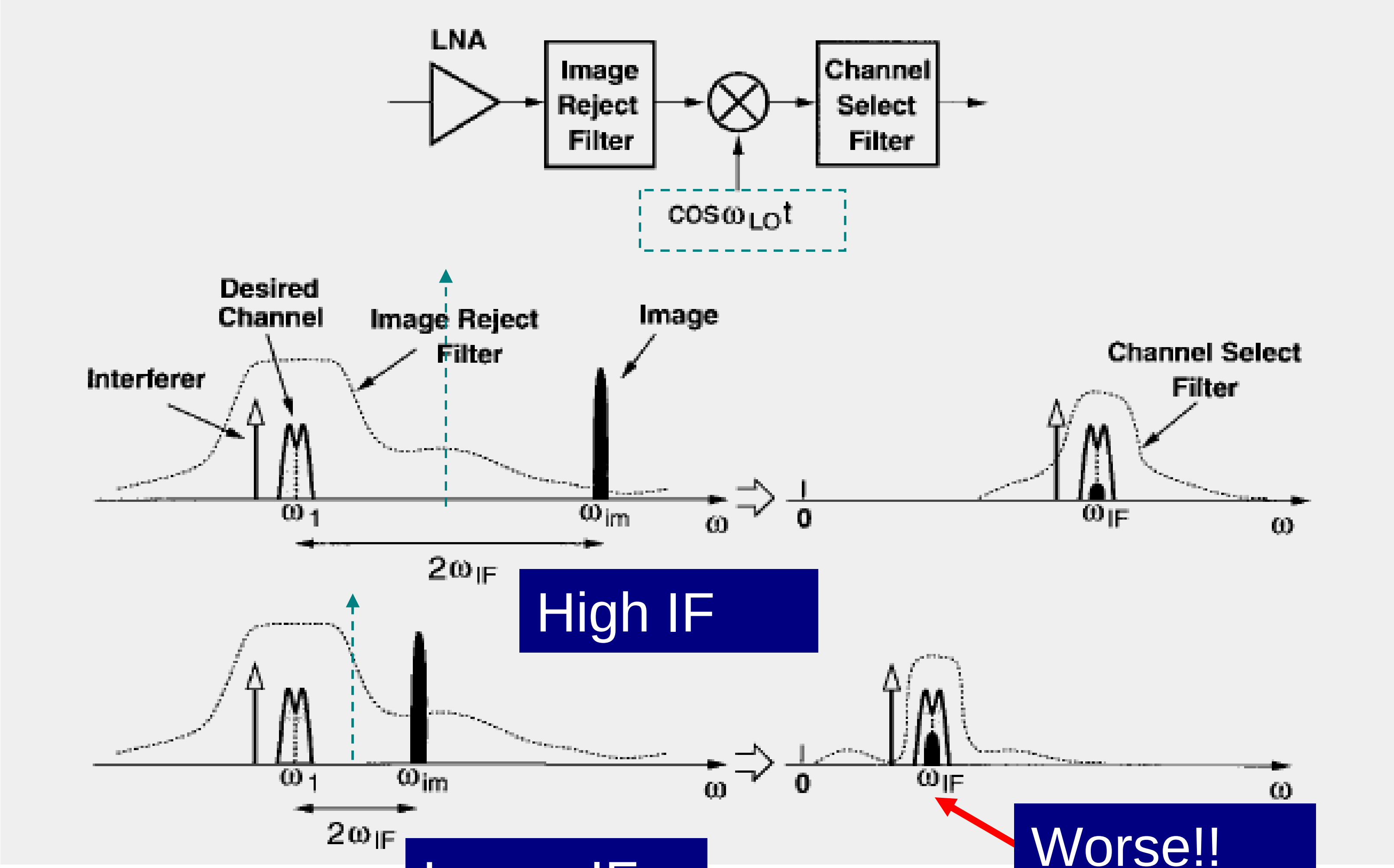
(or: Agilent ADS (licensed))


Difficult to integrate

Receiver Architecturese exploiting image filtering

Super-heterodyne receiver

Super-heterodyne receiver (I)



High IF

Lower IF

Worse!!

Image: B. Razavi

Super-heterodyne receiver (II)

Do downconversion in two steps (keep ω_{IF} relatively high compared to ω_{RF}, reducing image filter spec)

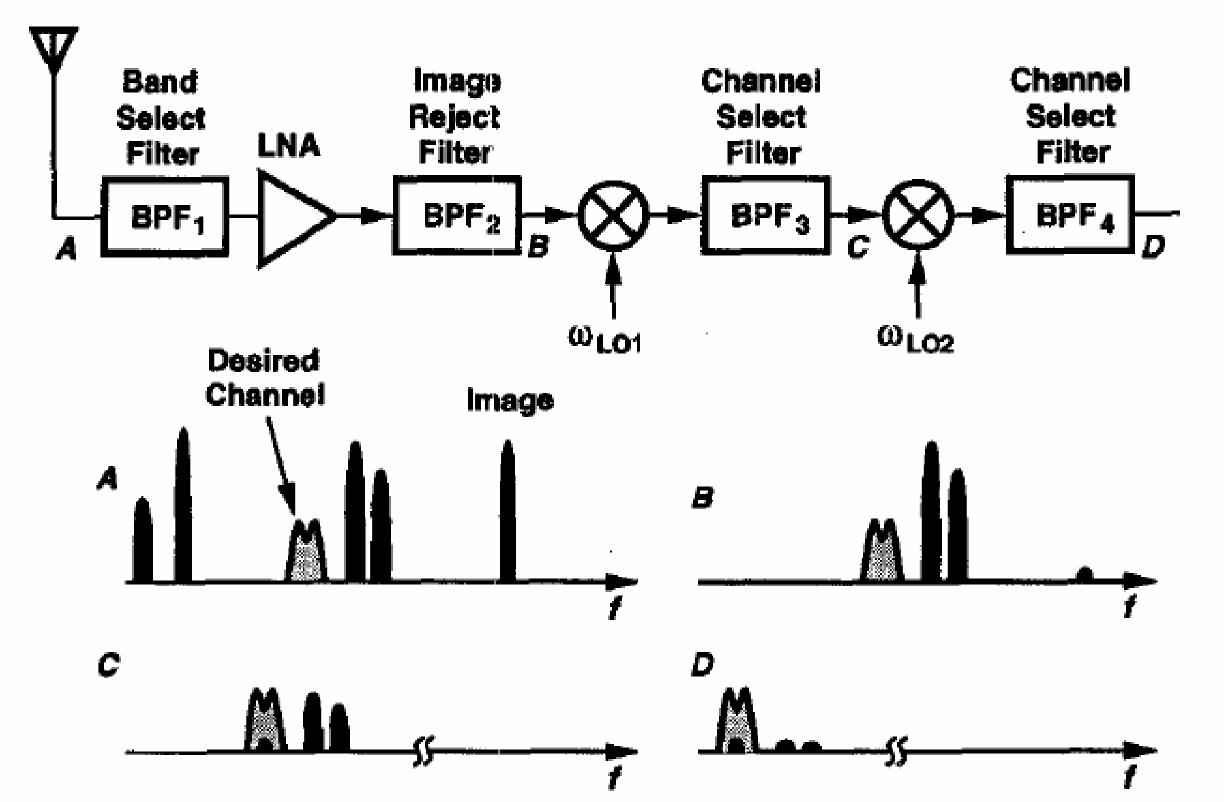


Image: B. Razavi

Pros & Cons Super-heterodyne receiver

Advantages:

- Amplify and filter at fixed frequency with dedicated high-Q passive filters => excellent selectivity and high rejection of strong interfering signals (passive filters).

Disadvantages:

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

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

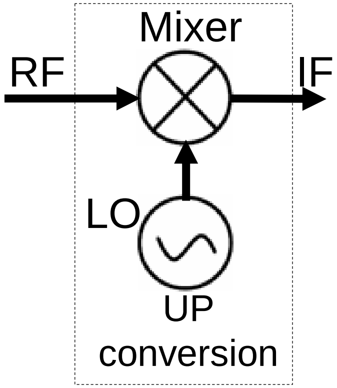
Source: V. Vidojkovic

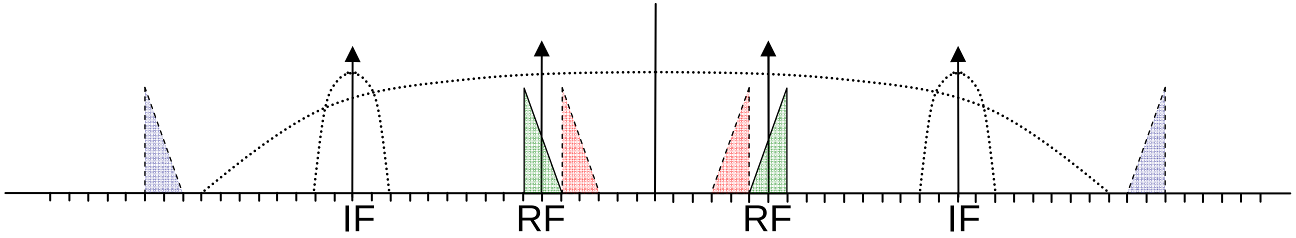
Even higher IF? Up-conversion!

Not difference but sum used: $\omega_{IF} = \omega_{RF} + \omega_{LO}$

Examples of use:

- Combining AM radio with FM radio (10.7MHz IF)
- Spectrum analysers: avoid overlap of input frequency measurement range with IF-band





Source: Kenneth Roovers

Direct-Conversion receiver

Direct-conversion receiver (“Homodyne”)

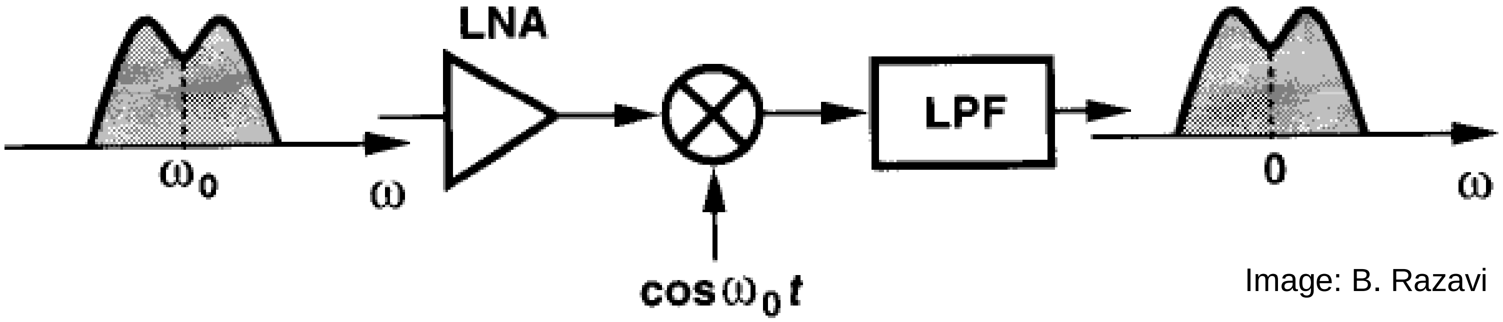


Image: B. Razavi

☺ Wanted channel converted around 0 Hz (“0-IF”)

☺ No external bandpass filter but simple low-pass filter => easy to integrate on a single-chip

☺ If the upper and lower sideband contain same information (e.g. for simple Double Sideband AM)

What if single sideband AM or PM or FM?

AM, PM and uncorrelated Sideband

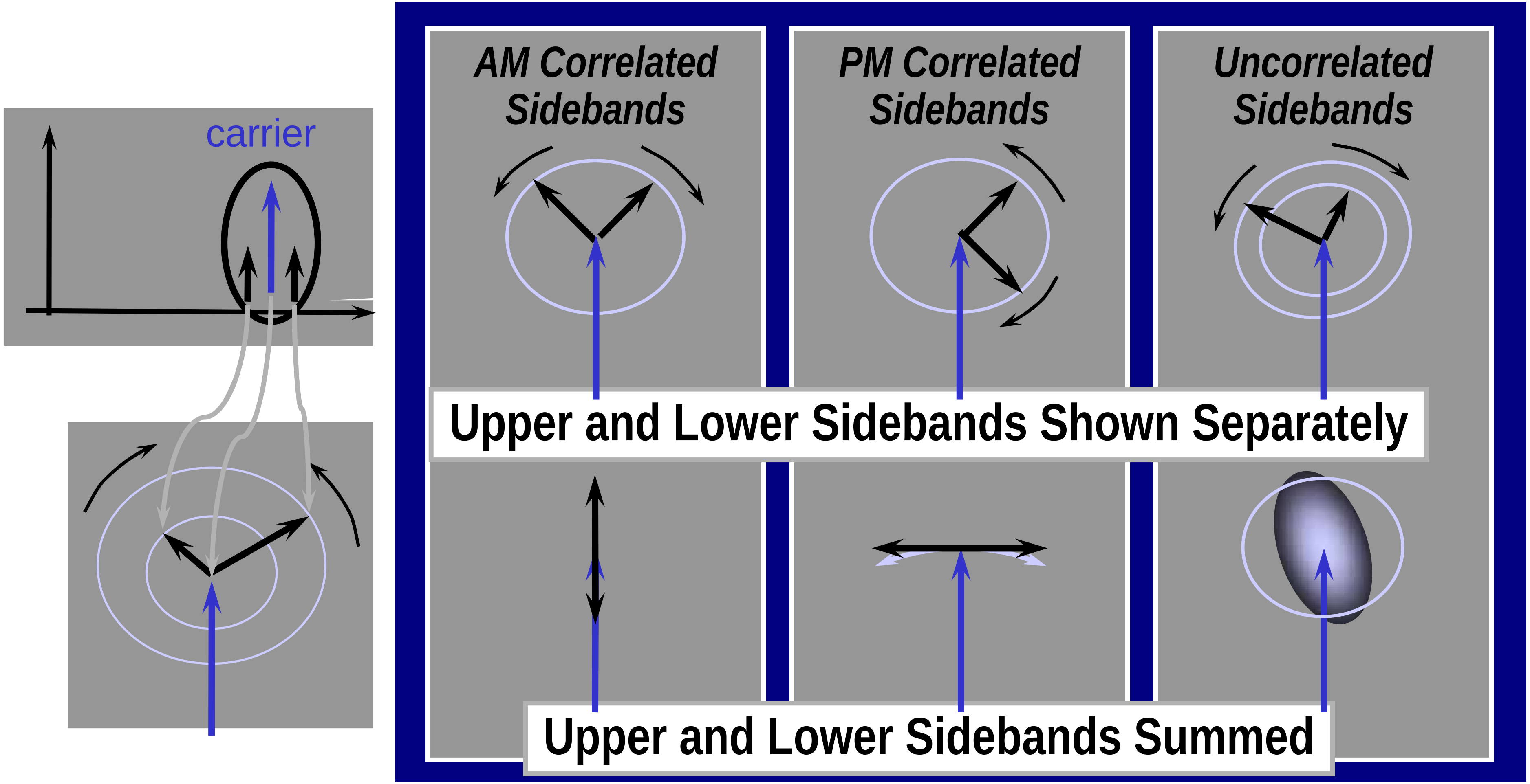
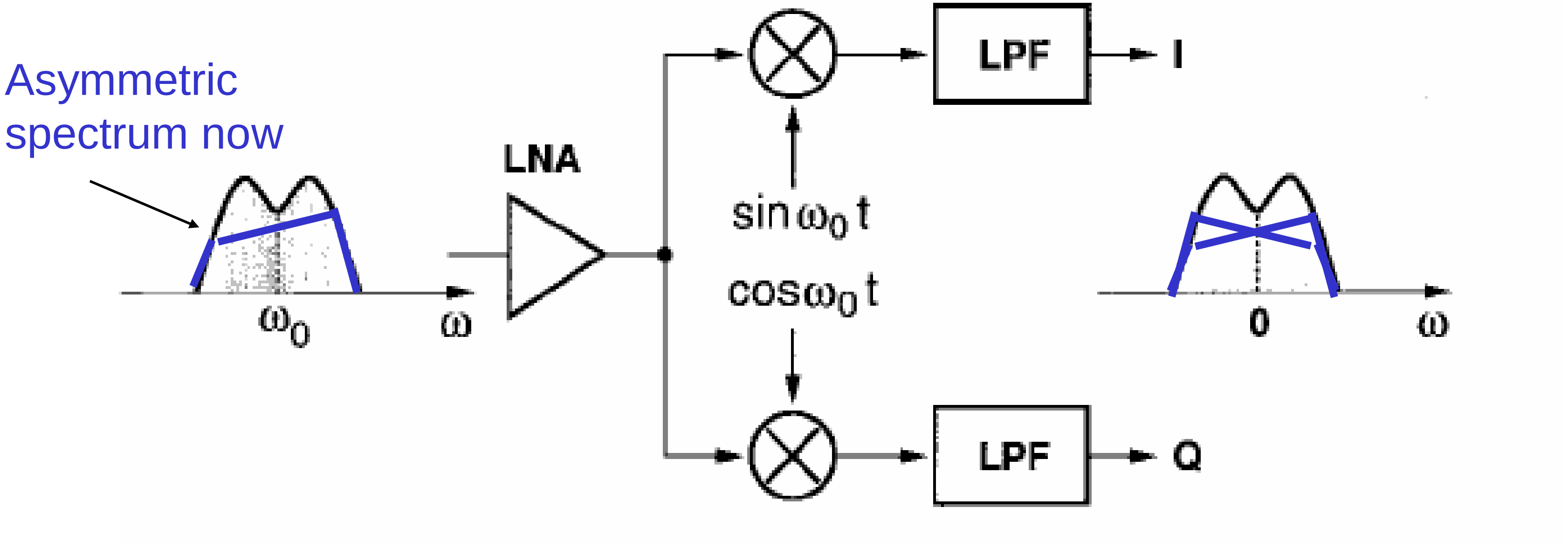


Image: K. Kundert

AM sideband are identical but not for PM or uncorrelated case!

Direct-conversion PM/FM receiver



Multiply both with a sine and a cosine (so all info known)

We do have an image problem now (proof in a few slides)

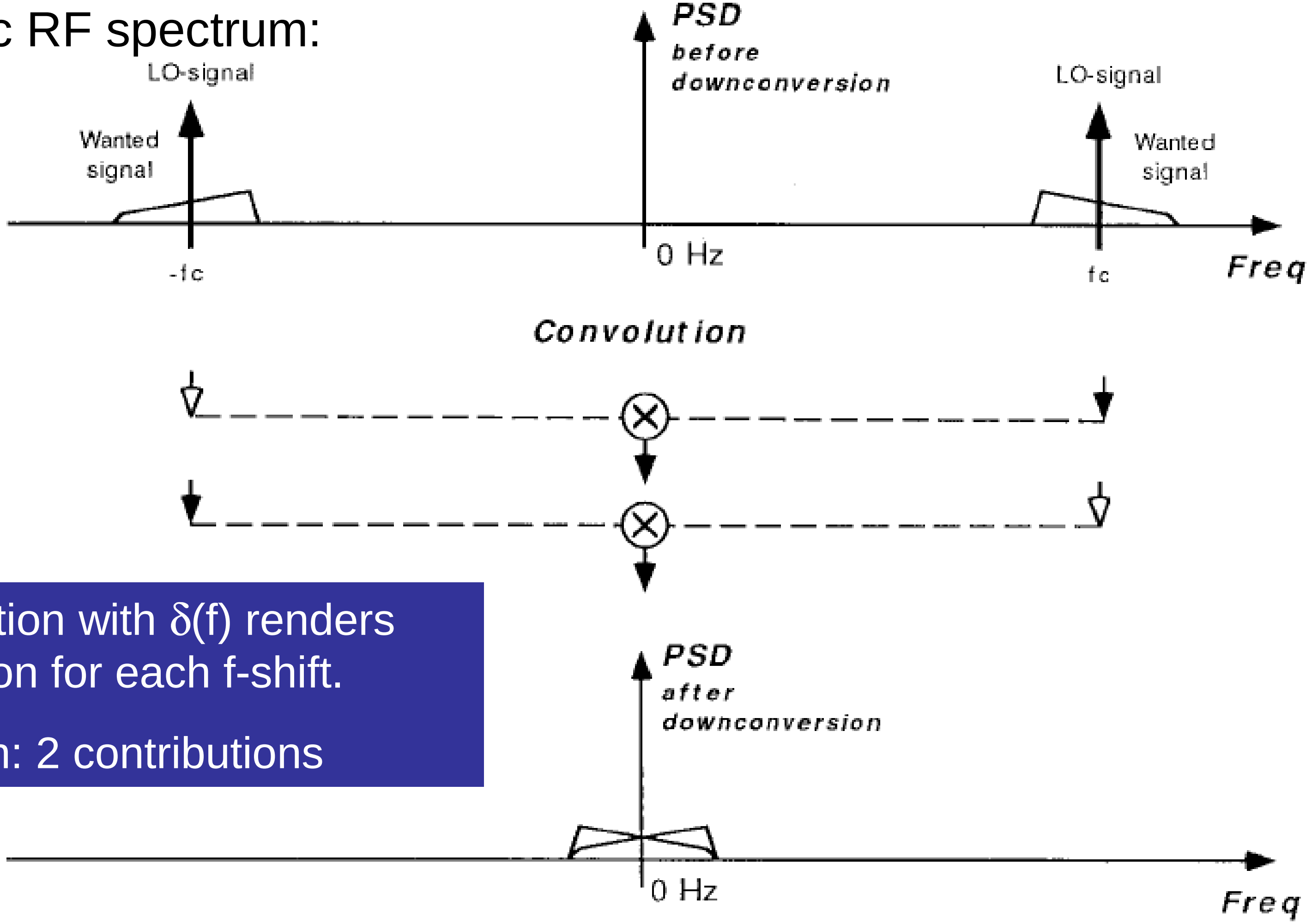
But can be solved easily because image has similar strength (no near/far problems with much stronger image)

Image-reject architectures

Direct Conversion Receiver: Complex Spectral View

Multiply in t-domain ⇔Convolution f-domain

Non-symmetric RF spectrum:



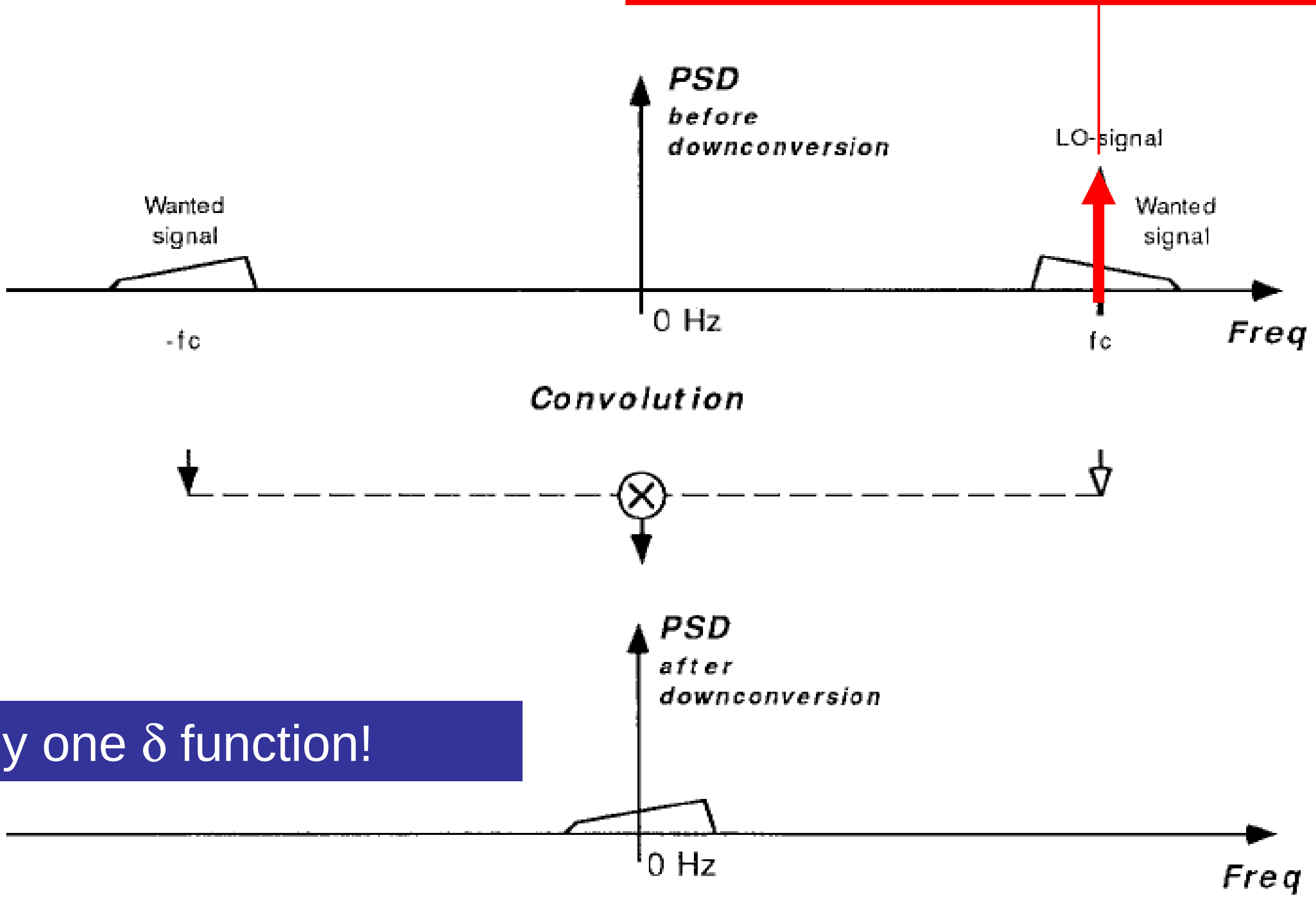
Note: convolution with δ(f) renders one contribution for each f-shift.

Two δ-function: 2 contributions

Source: Crols et al, TCASII

Solution: mix with one-sided LO-signal

$$\exp(j\omega t) = \cos(\omega t) + j\sin(\omega t)$$



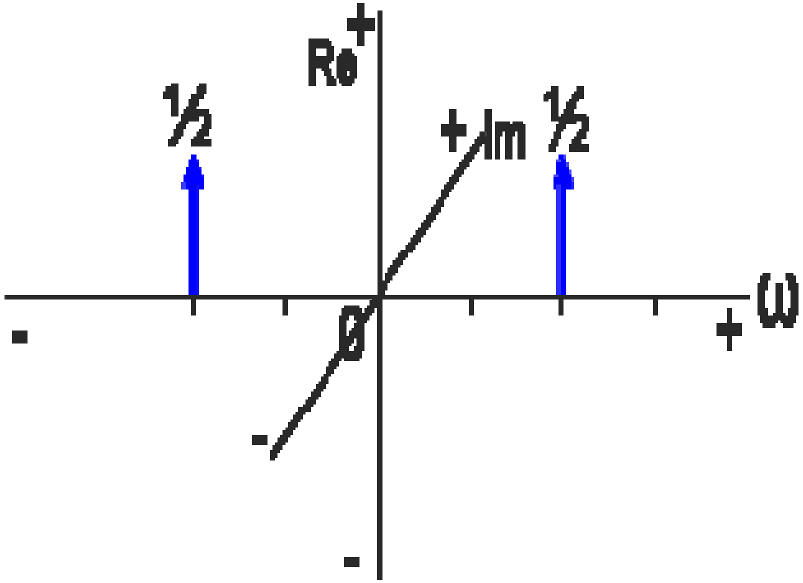
Only one δ function!

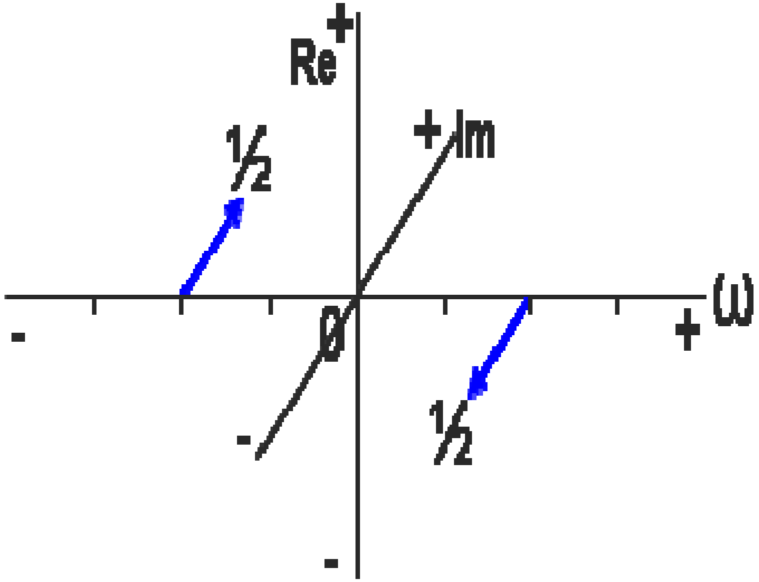
How can we generate a single sided δ(f)?

(Complex) Spectrum of cosine and sine

Complex spectral representation of cos and sin:

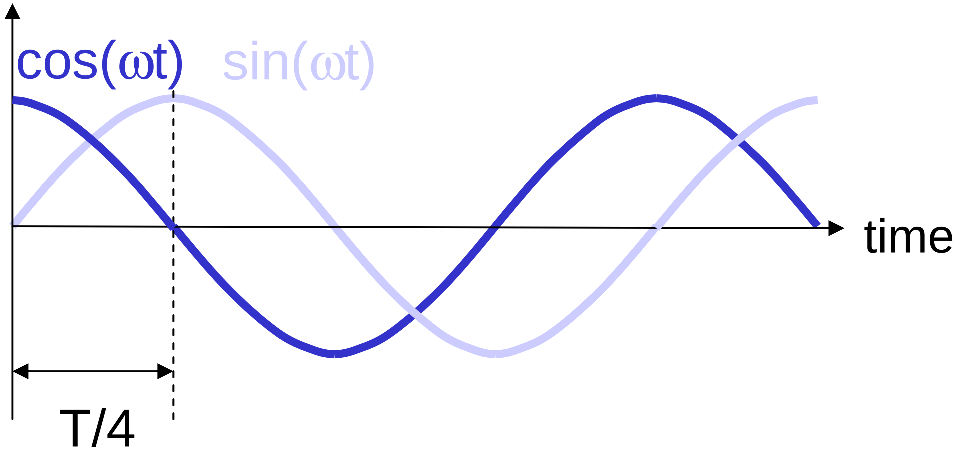
$$\cos(\omega t) = \frac{e^{-j\omega t}}{2} + \frac{e^{j\omega t}}{2} \qquad \sin(\omega t) = +j\frac{e^{-j\omega t}}{2} - j\frac{e^{j\omega t}}{2}$$





Source: Kenneth Roovers, MSc Thesis 06

T/4 delay or π/2 phase lag: from cosine to sine



$$\cos(\omega t) = \frac{e^{-j\omega t}}{2} + \frac{e^{j\omega t}}{2}$$

x j

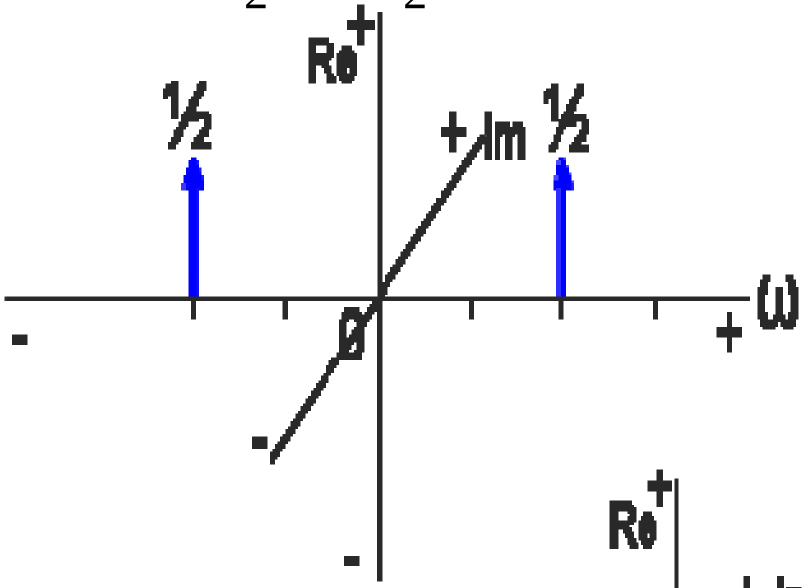
x -j

$$\sin(\omega t) = +j\frac{e^{-j\omega t}}{2} - j\frac{e^{j\omega t}}{2}$$

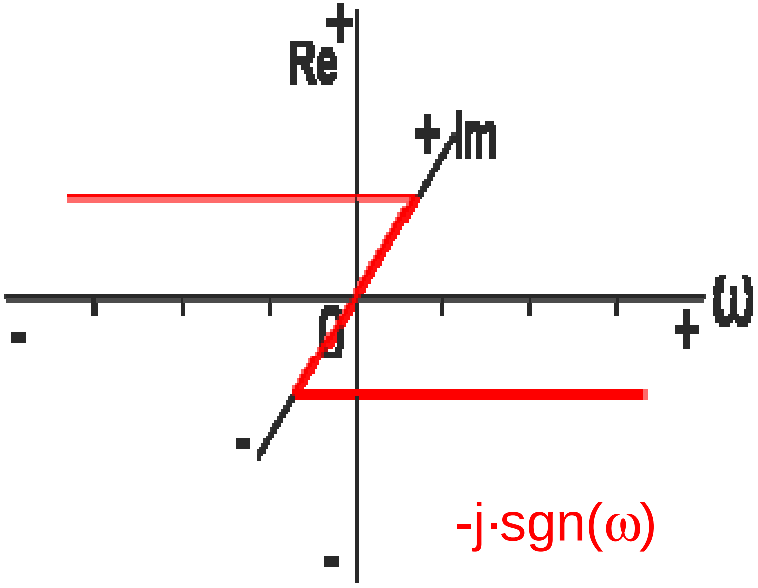
Equivalent to: multiply with -j·sgn(ω) (“Hilbert Transform”)

Graphical Representation

$$\cos(\omega t) = \frac{e^{-j\omega t}}{2} + \frac{e^{j\omega t}}{2}$$



X



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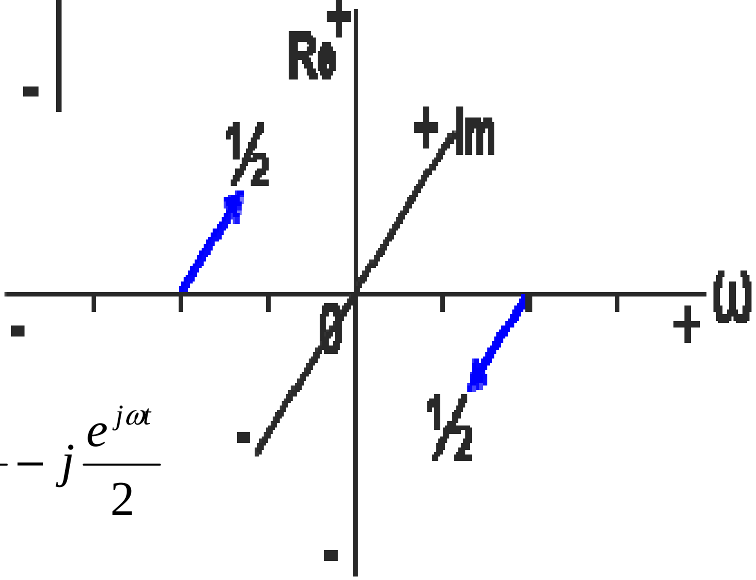


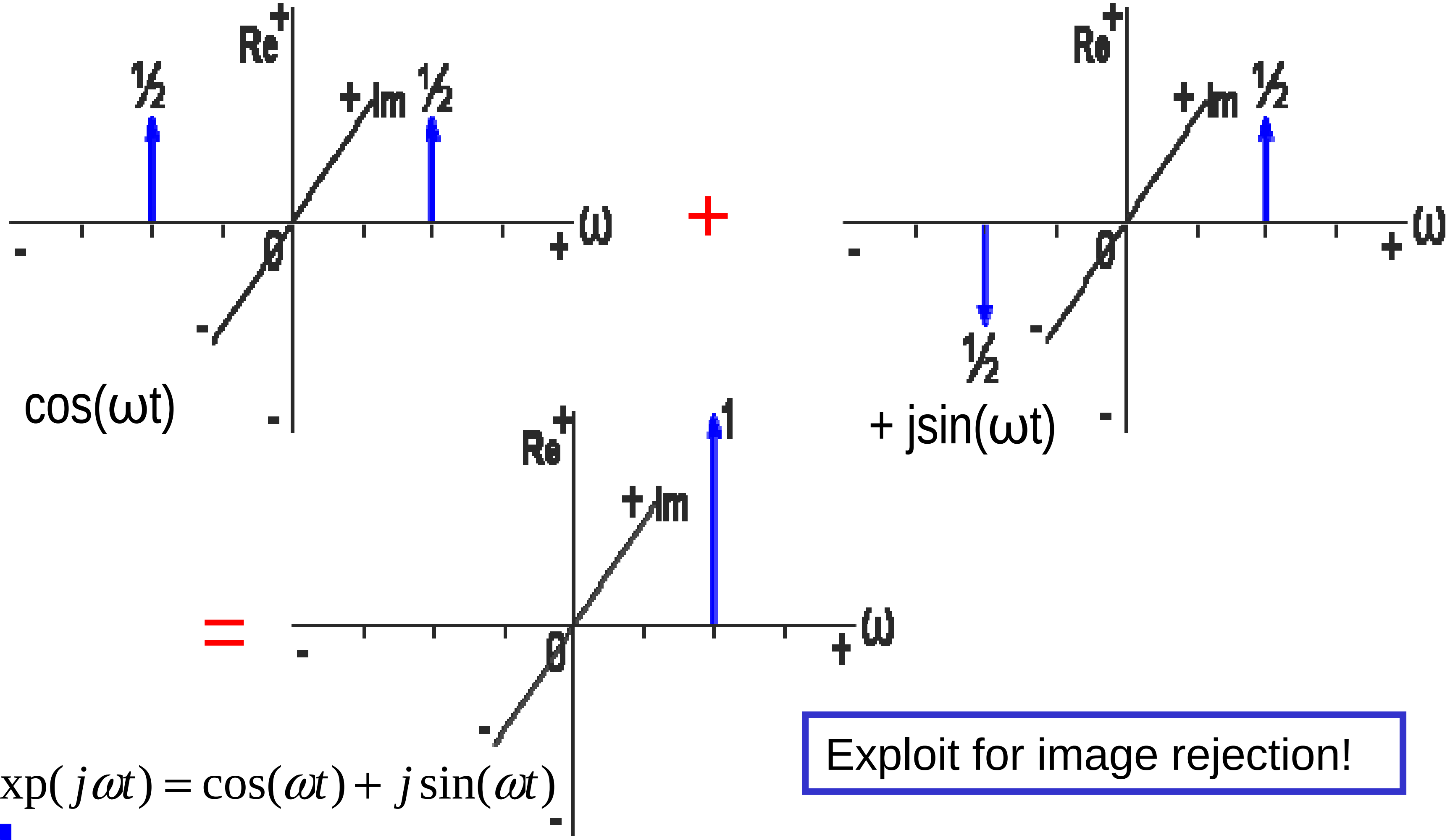
$$\sin(\omega t) = +j\frac{e^{-j\omega t}}{2} - j\frac{e^{j\omega t}}{2}$$

Useful manipulations!

- Re to Im
- different for + ω and -ω

Source: Kenneth Roovers, MSc Thesis 06

Example: Construct “single sided” exponential



$$\exp(j\omega t) = \cos(\omega t) + j\sin(\omega t)$$

Exploit for image rejection!

Reasons for I/Q or “Quadrature” signals?

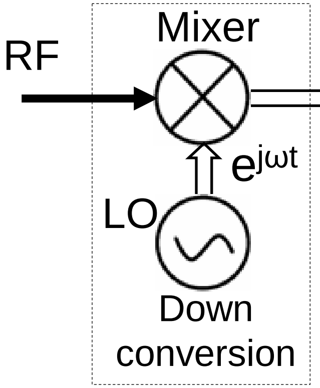
- Mathematical convenience (like polar/rectangular math)
- To design/analyze complex signals processing circuits (requires 2 real signals to represent I + jQ)

“In-phase” or

“Cosine-channel”

“Quadrature”

or “Sine-channel”



- E.g.: for image rejection multiply with:

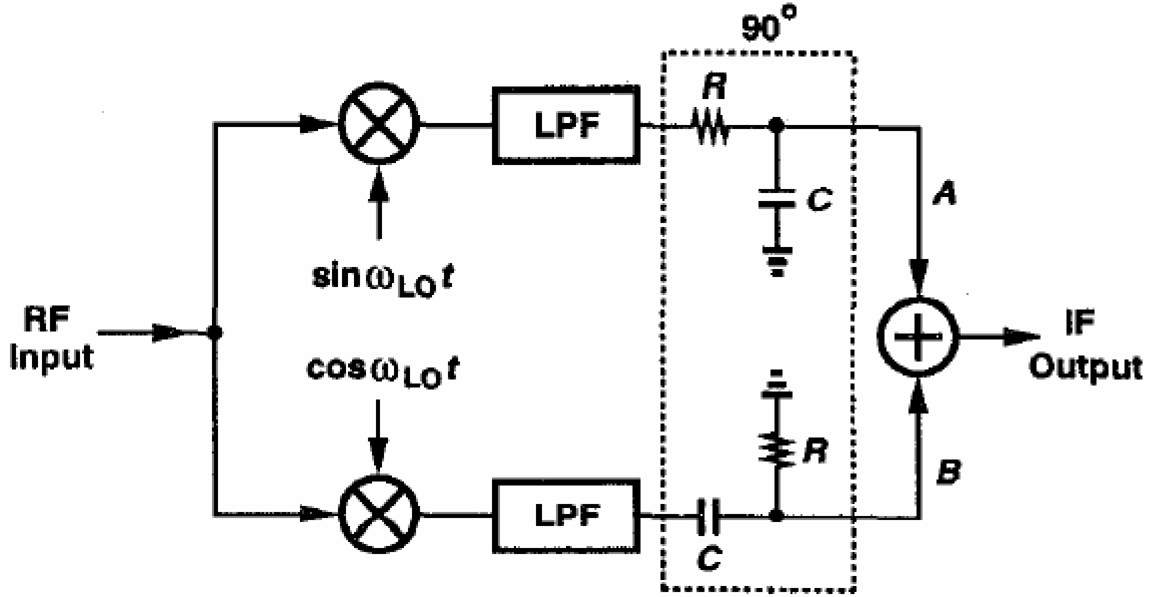
$$\exp(j\omega t) = \cos(\omega t) + j\sin(\omega t)$$

Hartley image-reject receiver

Functions:

- mulipIy with cosine
- multiply with sine and give -90 degree phase shift

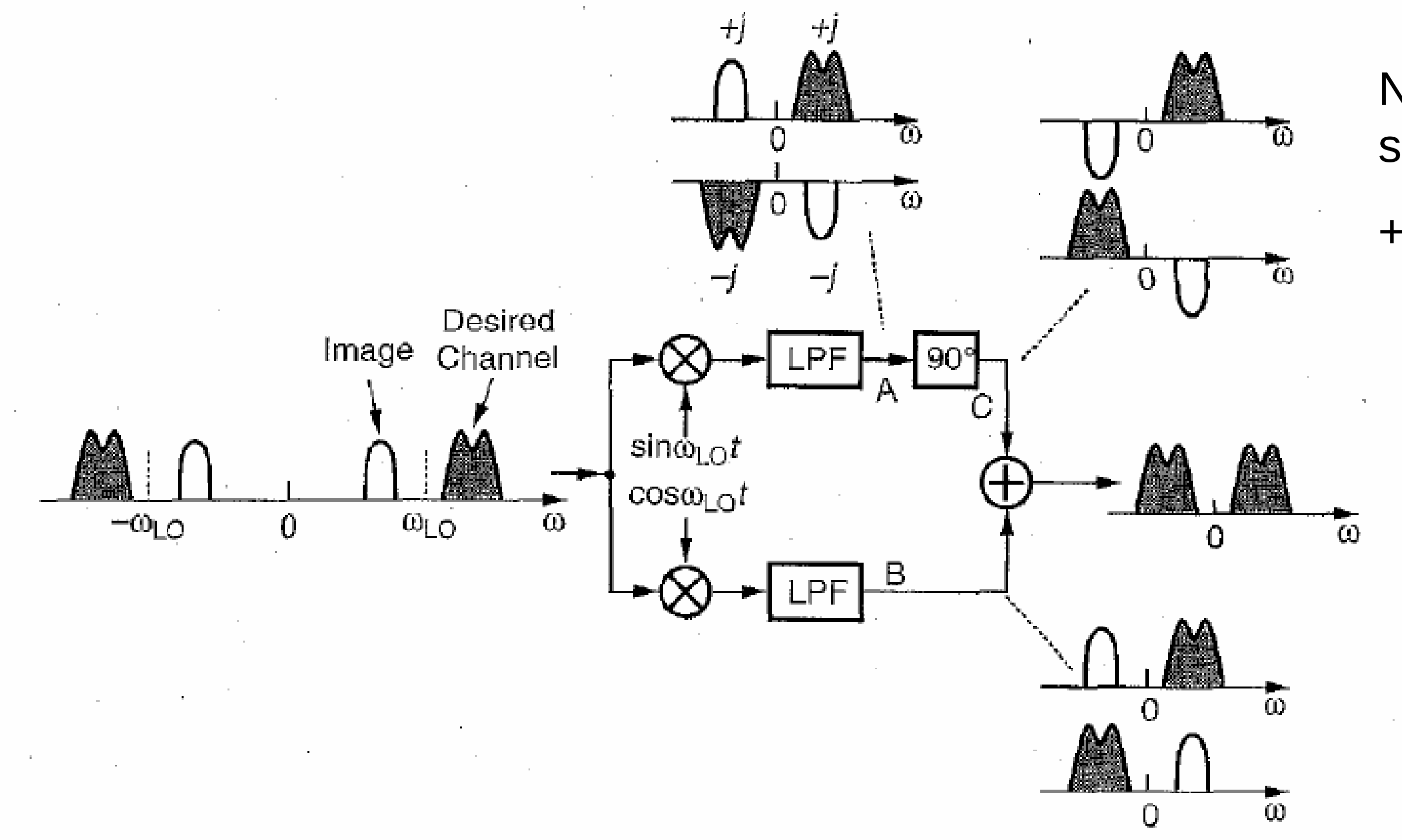
Summed signal is free from image under perfect matching



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

Image: B. Razavi

Spectra in Hartley architecture



Note: separetely show contribution of

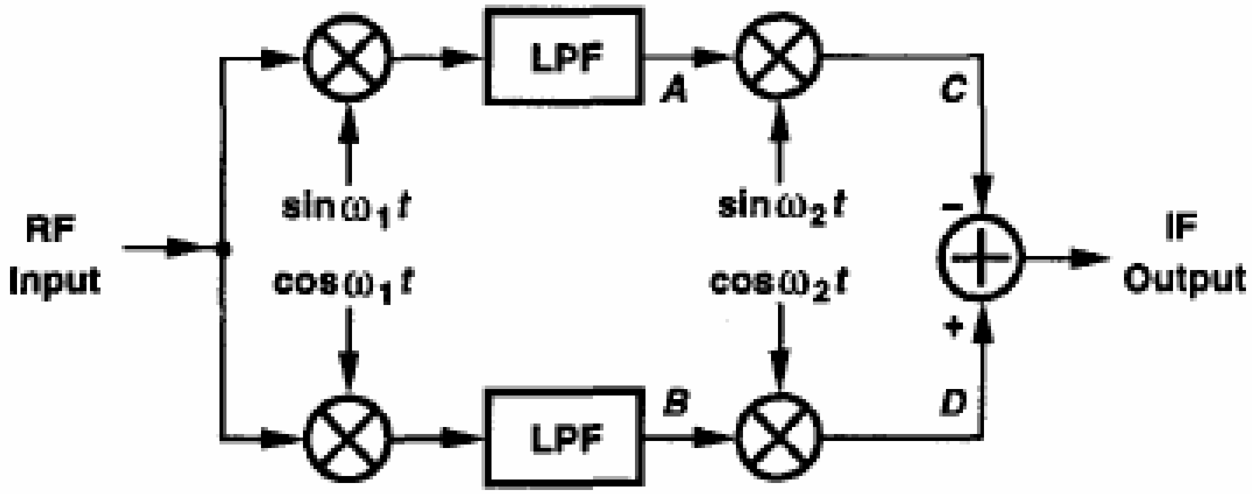
$+\omega_{LO}$ and $-\omega_{LO}$

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

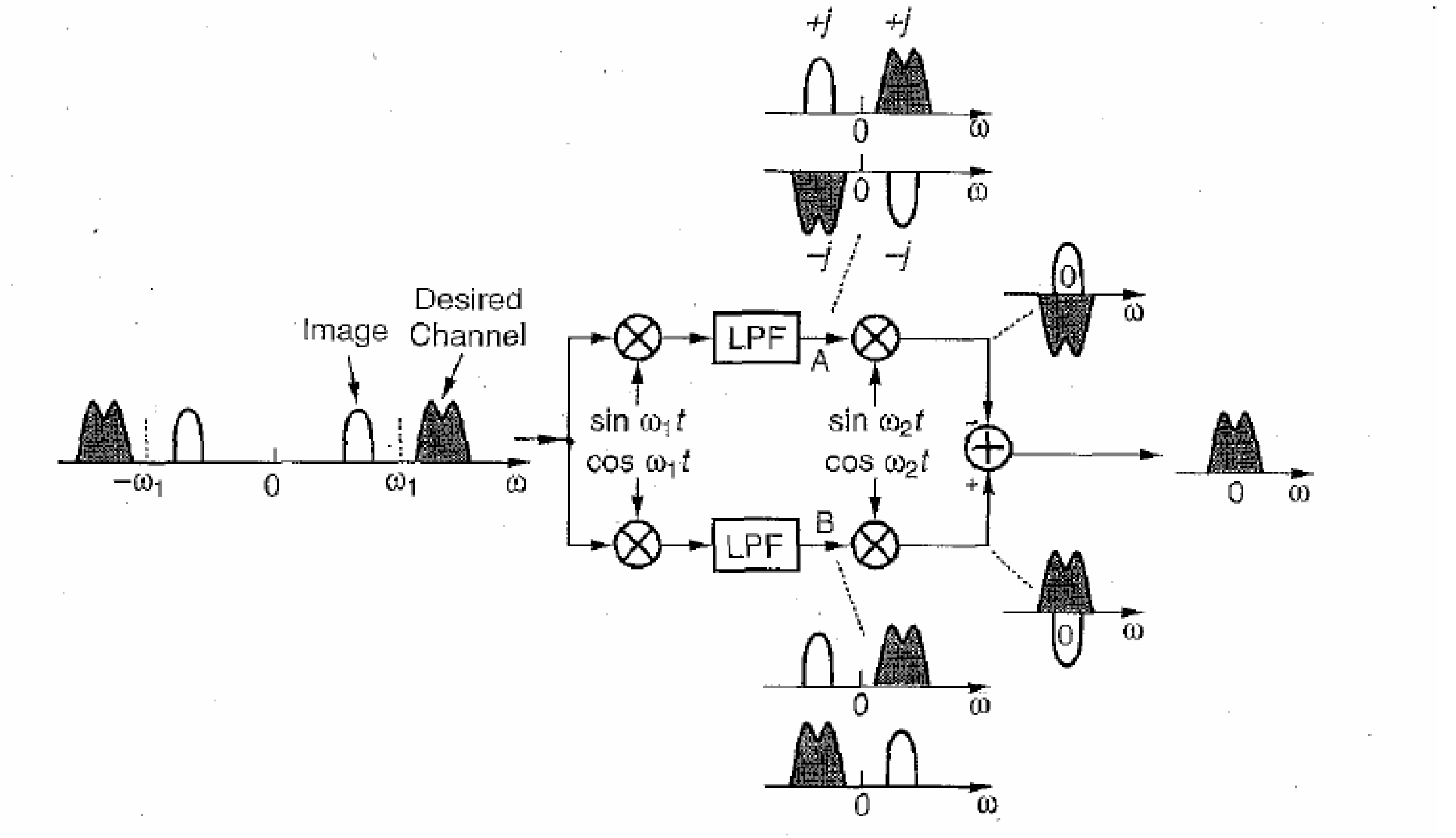


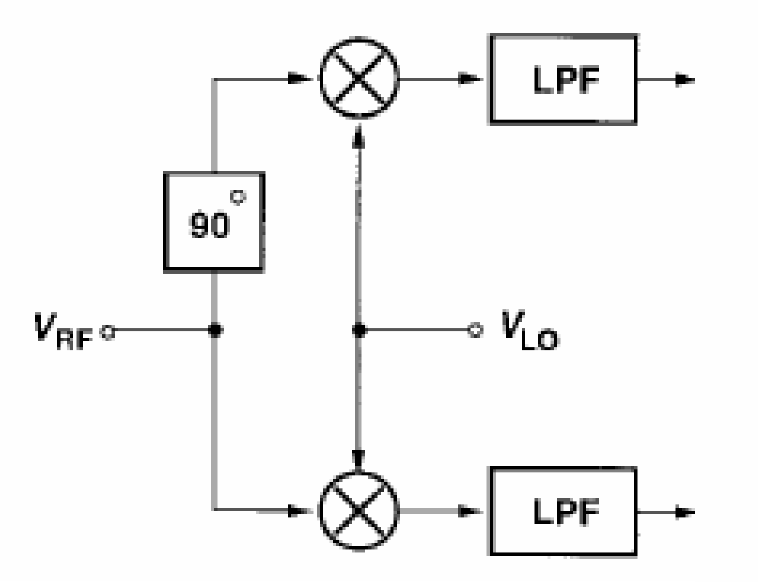
Image: B. Razavi

Limitations

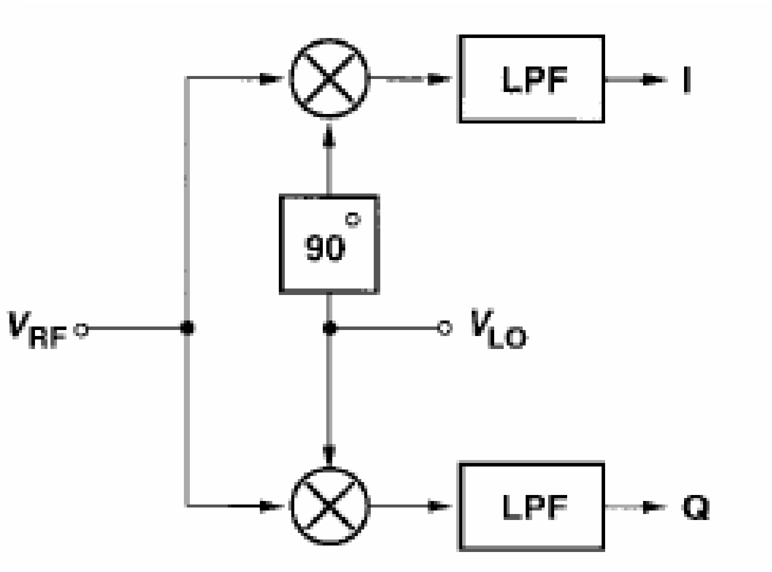
on Image Rejection

Options for I/Q generation: in RF or LO path

Only relative phase RF versus LO matters:



I/Q generation in RF path



I/Q generation in LO path

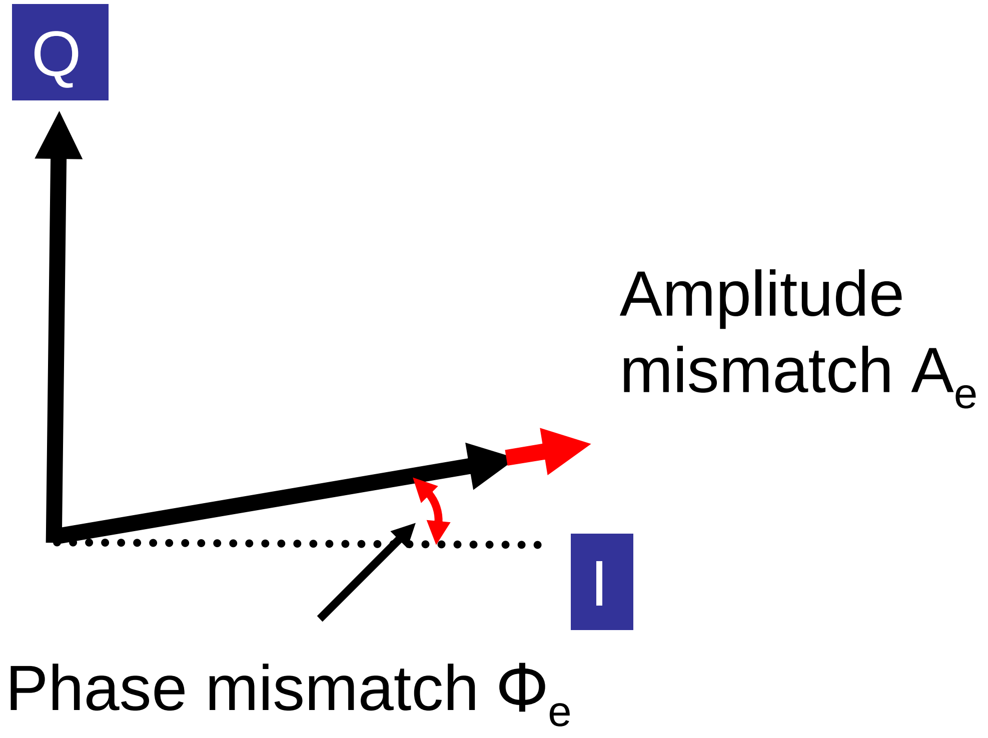
Often I/Q generation in the LO path preferred:

- Avoid adding noise in RF path
- Often square-wave LO: more I/Q generation options (see slides on LO generation from previous lecture)

Image: B. Razavi

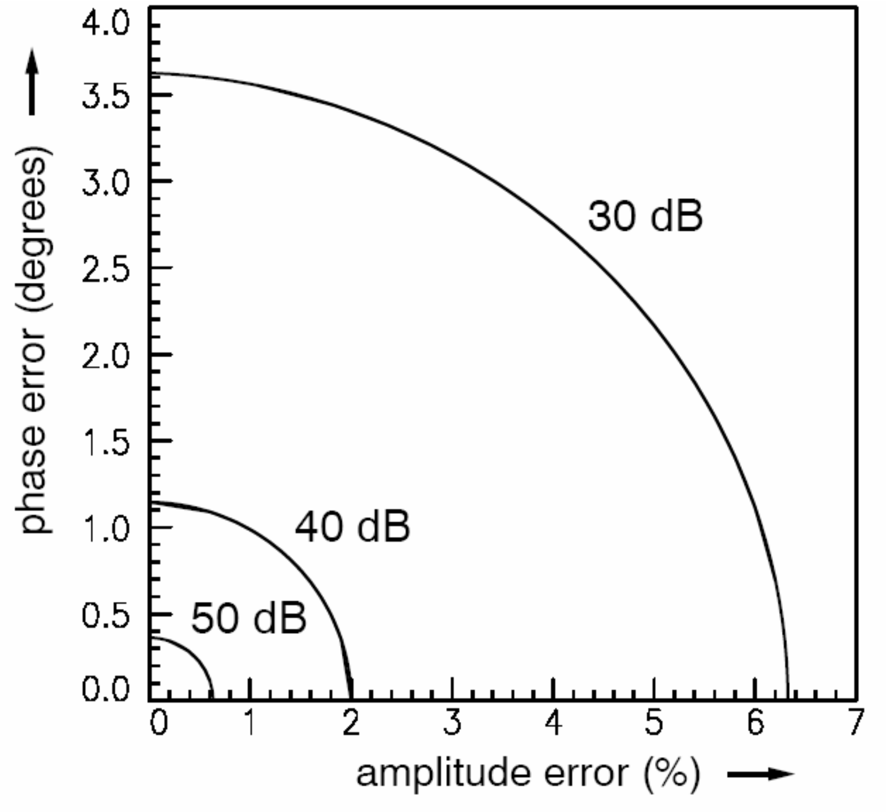
Design issues of direct-conversion: I/Q mismatch

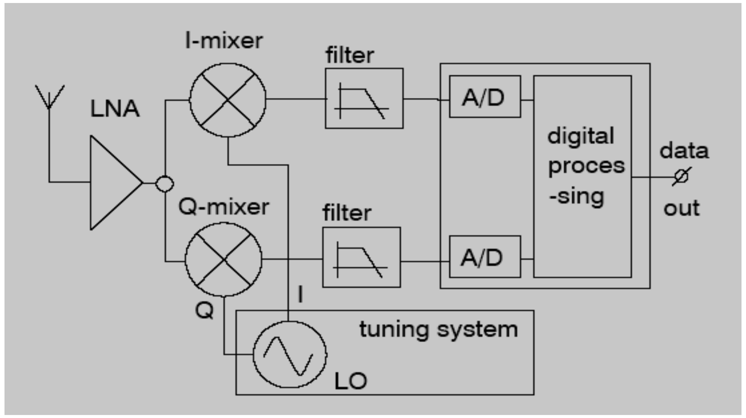
Cross-talk (image-problem) when there is amplitude or phase mismatch between the I and Q channel.



I/Q Amplitude/Phase mismatch and IRR

IRR = Image Reject Ratio (10log($P_{image}/P_{wanted)}$)





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

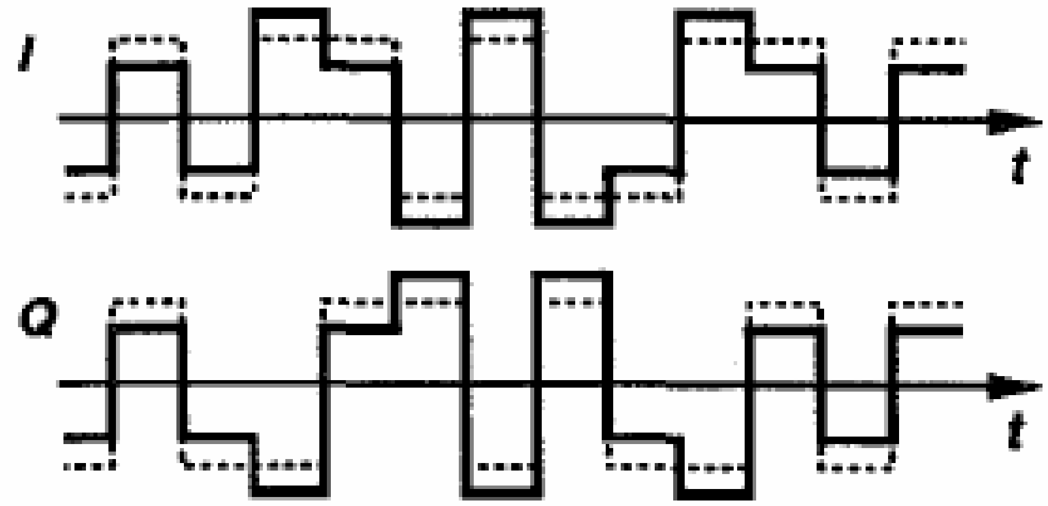
Amplitude error

Phase error

Effect of I/Q mismatch on QPSK

I-data partly visible in Q also reversely:

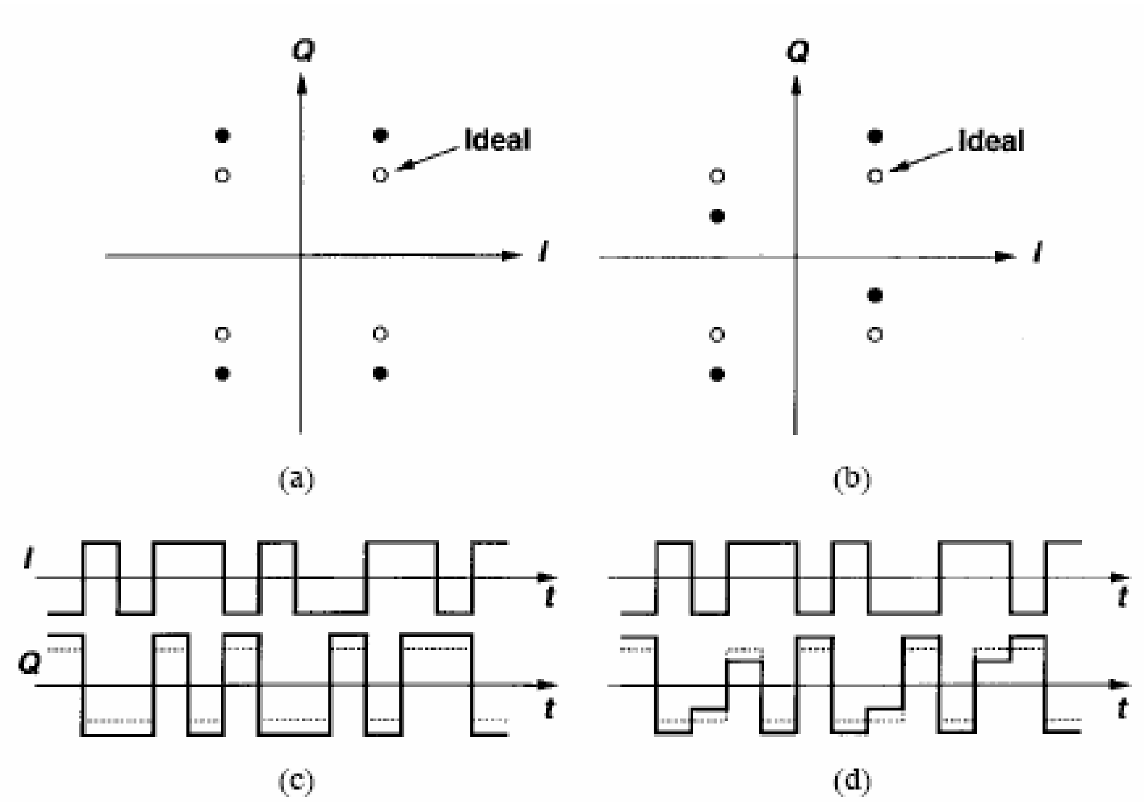
Demodulated QPSK data



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

Image: B. Razavi

I/Q mismatch and QPSK constellation diagram



Effect of gain mismatch

Effect of phase mismatch

Image: B. Razavi

Flashback on Reasons for using Quadrature

Different functional motivations:

- Spectral efficiency: Orthogonal modulation I and Q (2x datacapacity)
- Select/Reject a sideband (e.g. upper or lower sideband)
- Fast measurement: Instanteneous amplitude measurement for cases where phase is not known:

$$A(t) = \sqrt{I(t)^2 + Q(t)^2}$$

What information does quadrature mixing bring?

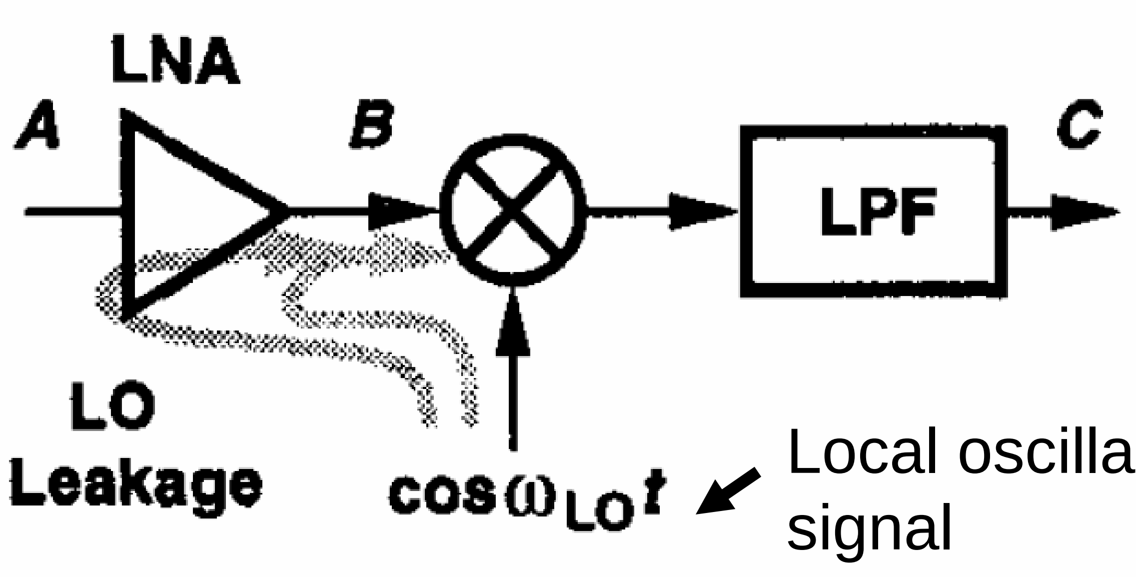
- Distinguish between positive and negative frequencies (useful for image rejection: upper/lower sideband)
- Complete knowledge of the signal (knowing I(t) and Q(t) means knowing both A(t) and phase ϕ(t))

Limitations

of 0-IF

Receivers

Design issues of direct-conversion: LO leakage

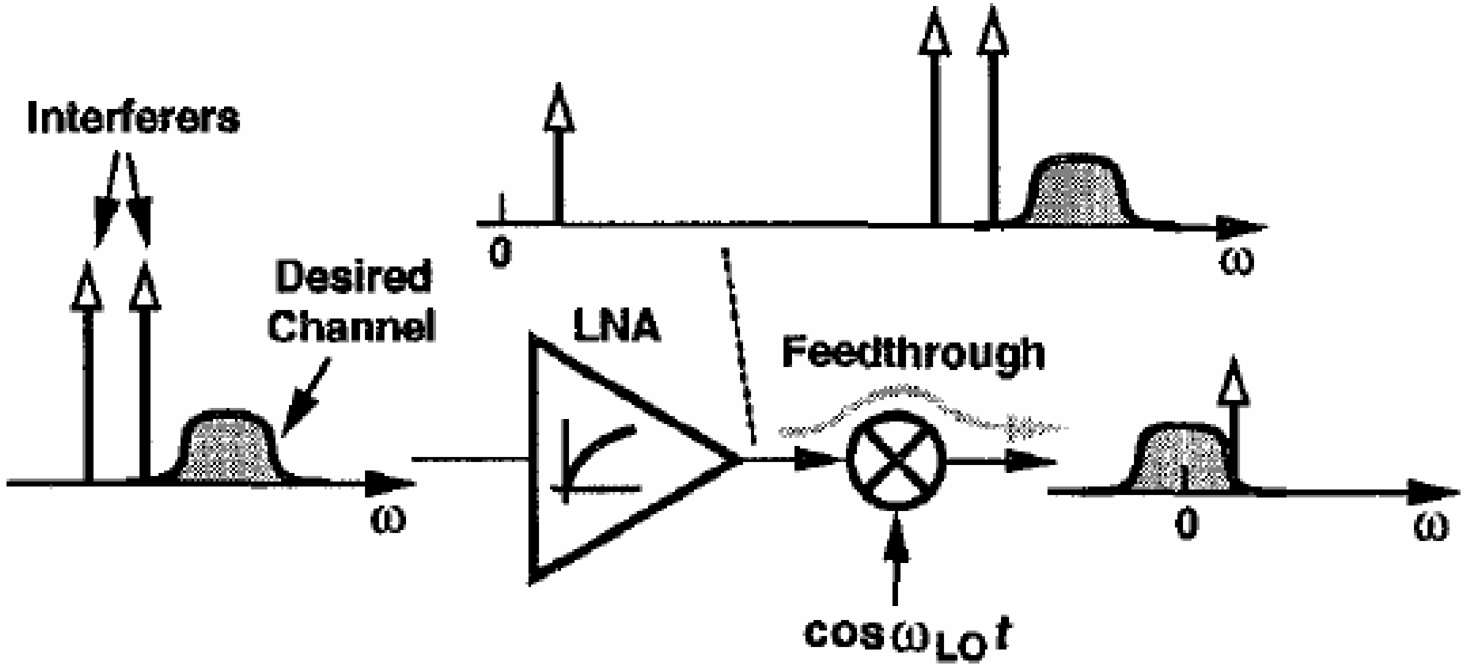


Local oscillator signal

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 easily by AC-coupling if there is a lot signal content (energy) located around DC.

Image: B. Razavi

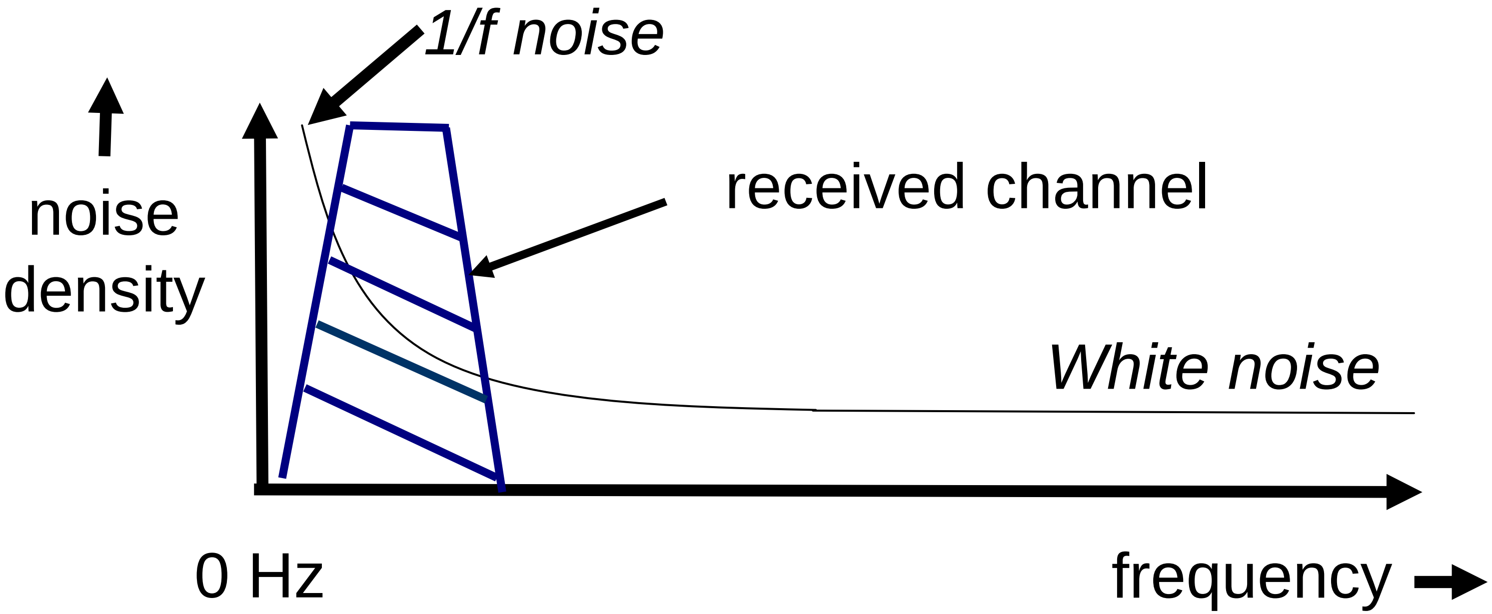
Design issues of direct-conversion: IM2 products



Even-order distortion creates low-frequency “beat notes” (modulated low frequency tones)

E.g. LNA IM2 term that leaks through mixer (mismatch)

Design issues of direct-conversion: 1/f noise



Especially for CMOS transceivers, 1/f noise can pose big problems!

Received signal has to compete with the 1/f noise!

Direct-conversion: frequently used

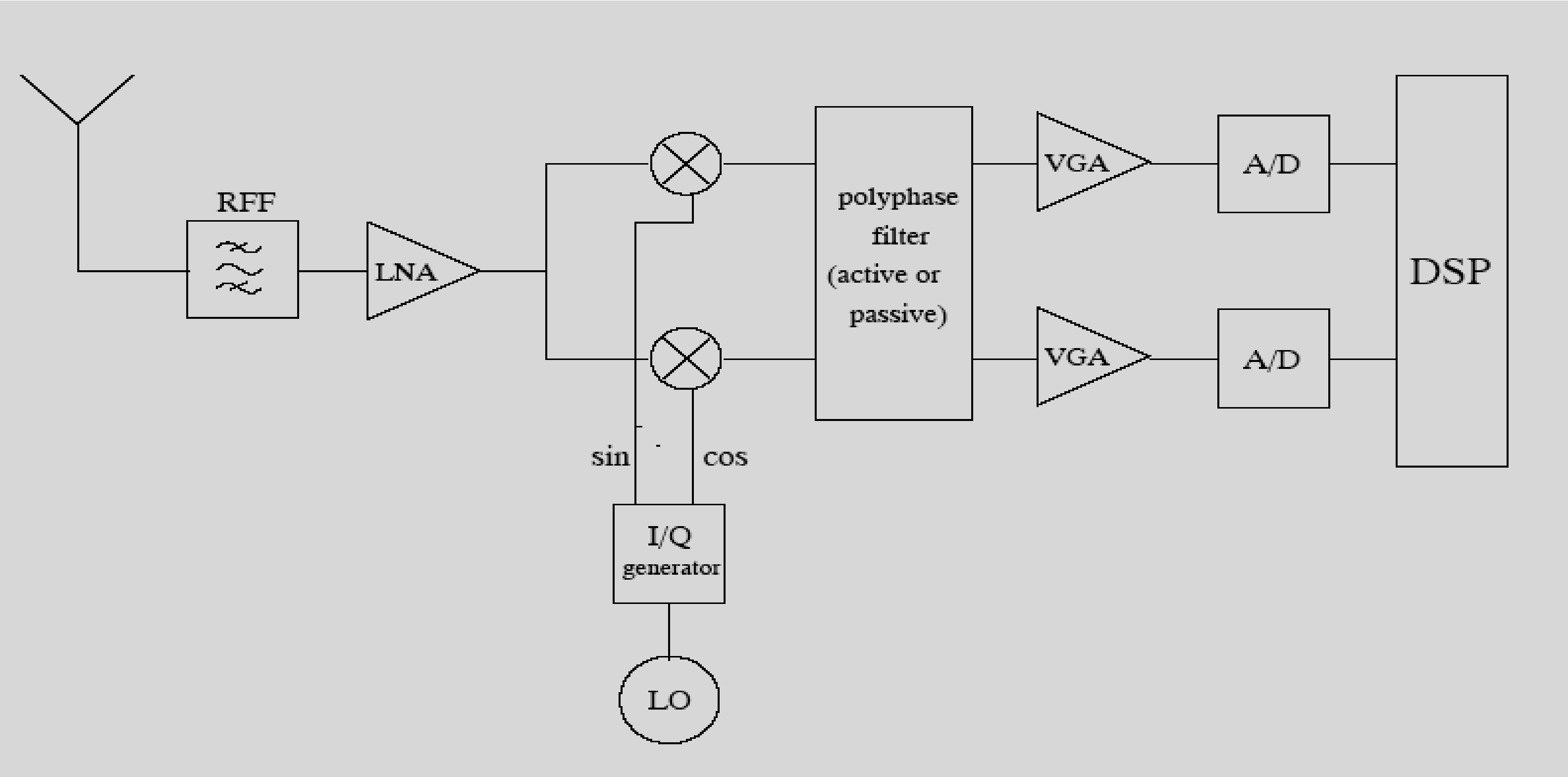
- Despite the many design challenges direct-conversion receivers face, they are used in many products.

- 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 bulky and relatively expensive

Low-IF receivers

Low-IF receiver



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

Image: V. Vidojkovic

Down conversion – Zero-IF

Source: Kenneth Roovers, MSc Thesis 06

RF spectrum:

LO spectrum:

Processing:

Final result:

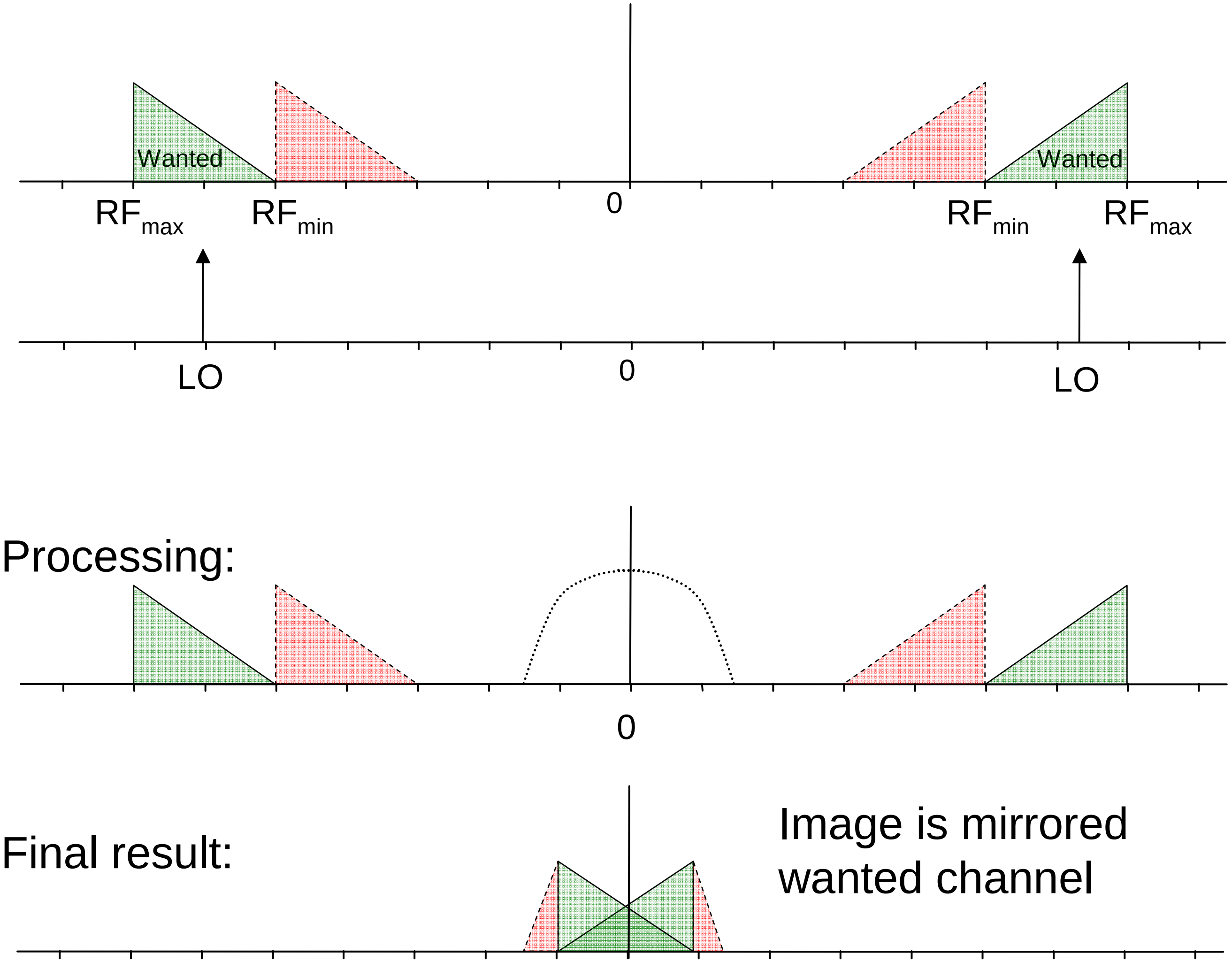
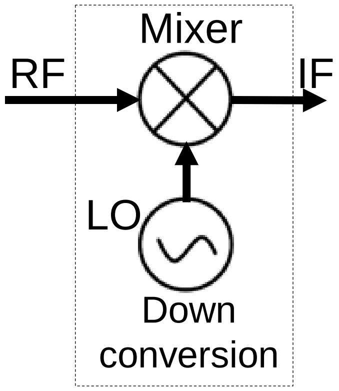


Image is mirrored wanted channel



Down conversion – Low-IF

Source: Kenneth Roovers, MSc Thesis 06

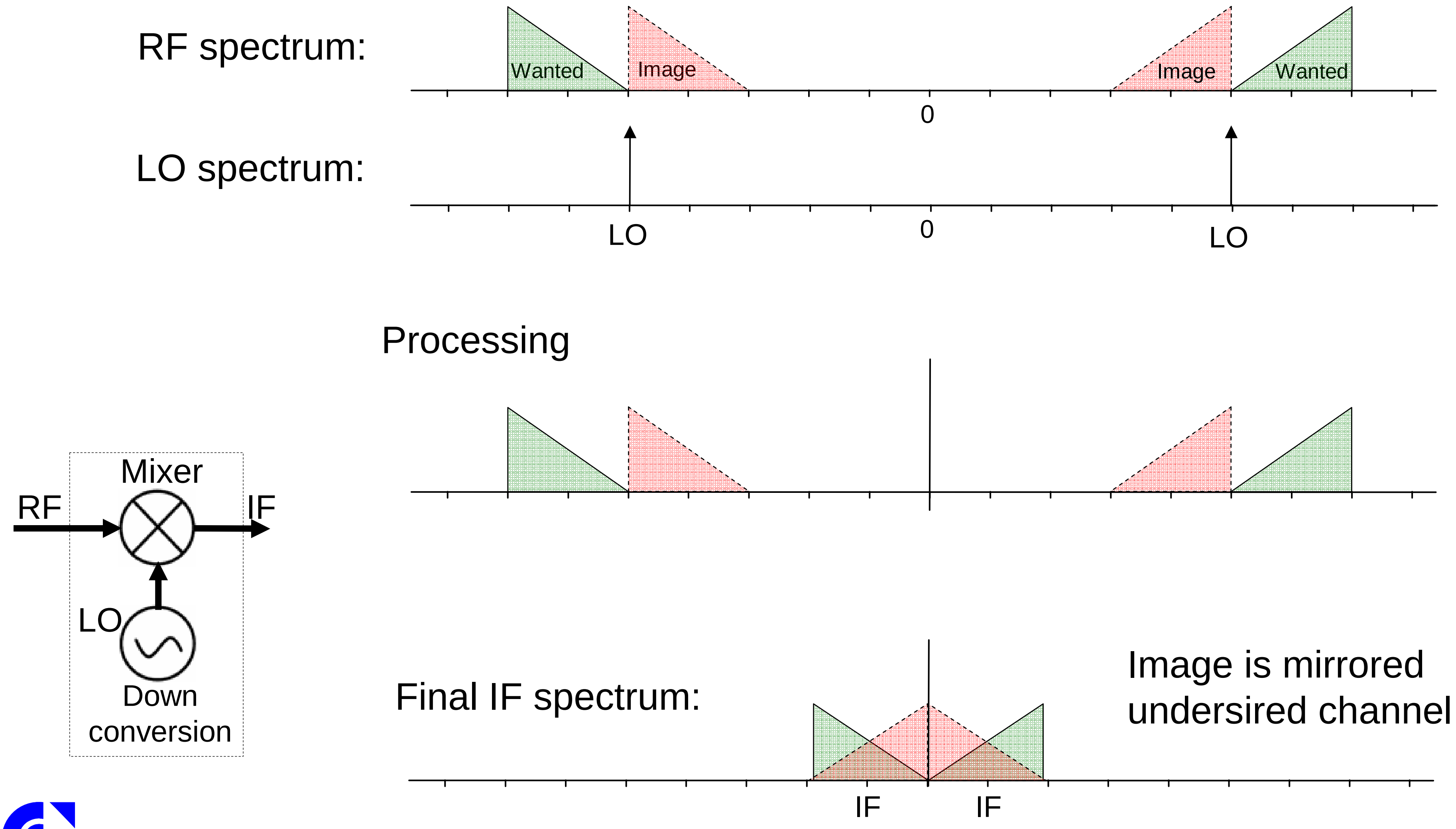
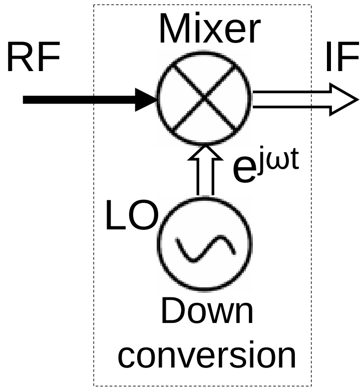


Image is mirrored undersired channel

Down conversion – complex (quadrature) mixing

Source: Kenneth Roovers, MSc Thesis 06

Quadrature mixer suppresses image ±40 dB depending on mismatch



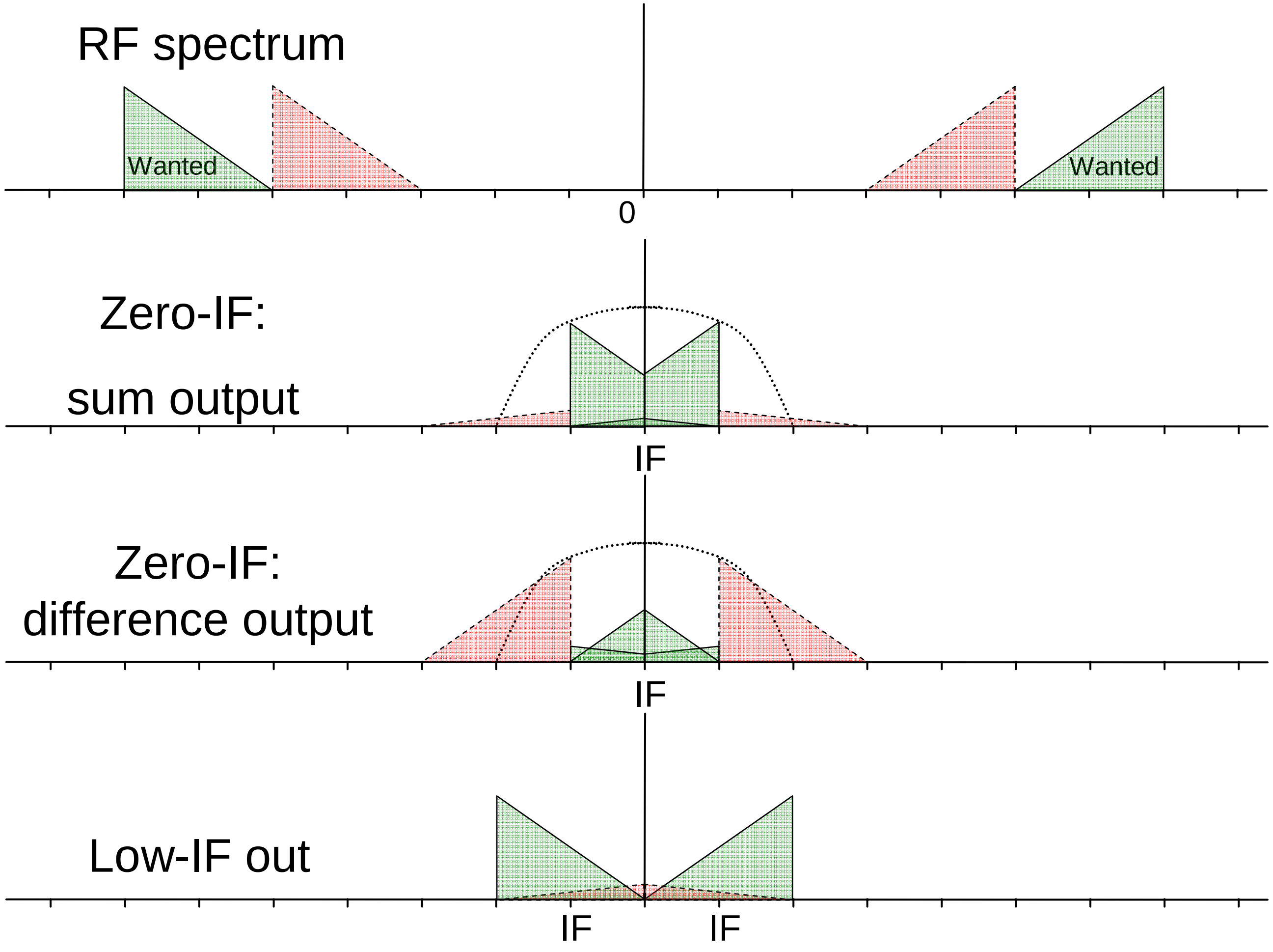
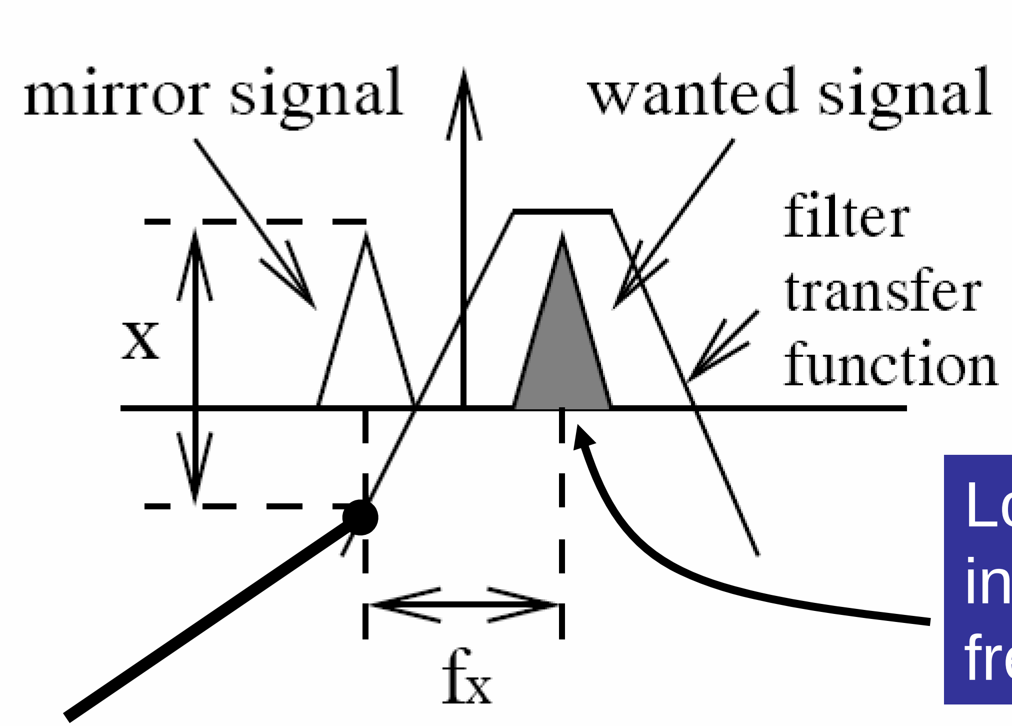


Image suppression by a poly-phase filter



Low-intermediate frequency

A poly-phase filter exploits I- and Q-phase signals to get an asymmetric transfer function with respect to 0 Hz

(different transfer for positive and negative frequencies)

Pros/Cons Low-IF receiver

☺ Image is suppressed by a poly-phase filter, which can be integrated.

☹ Because of mismatch, 30-35 dB image suppression is typical

☺ The IF-frequency is low but not 0 Hz, hence less or no 1/f noise

☺ High-pass filter after the mixer can remove unwanted Low Freq. signals (spectrum around DC shouldn’t contain crucial info)

☹ Limited image suppression is not always enough (choose IF at adjacent channel distance to relaxed requirement)

☹ Poly-phase filters more power-hungry then low-pass filters

☹ Poly-phase filters may require a lot of chip area (complex transfer function; use large capacitors, because of the low-IF).

☹ Even-order distortion components may still produce unwanted “beat notes” in the wanted channel, after down-conversion (via even order disto AM-envelope of strong interferers is detected)

Digital-IF Receiver

Digital-IF Receiver

Advantage digital I/Q generation: I/Q matching can be improved arbitrarily by using more bits.

If very high image rejection (e.g. 60-80dB) needed: still possible in principle, provided the ADC is good enough!

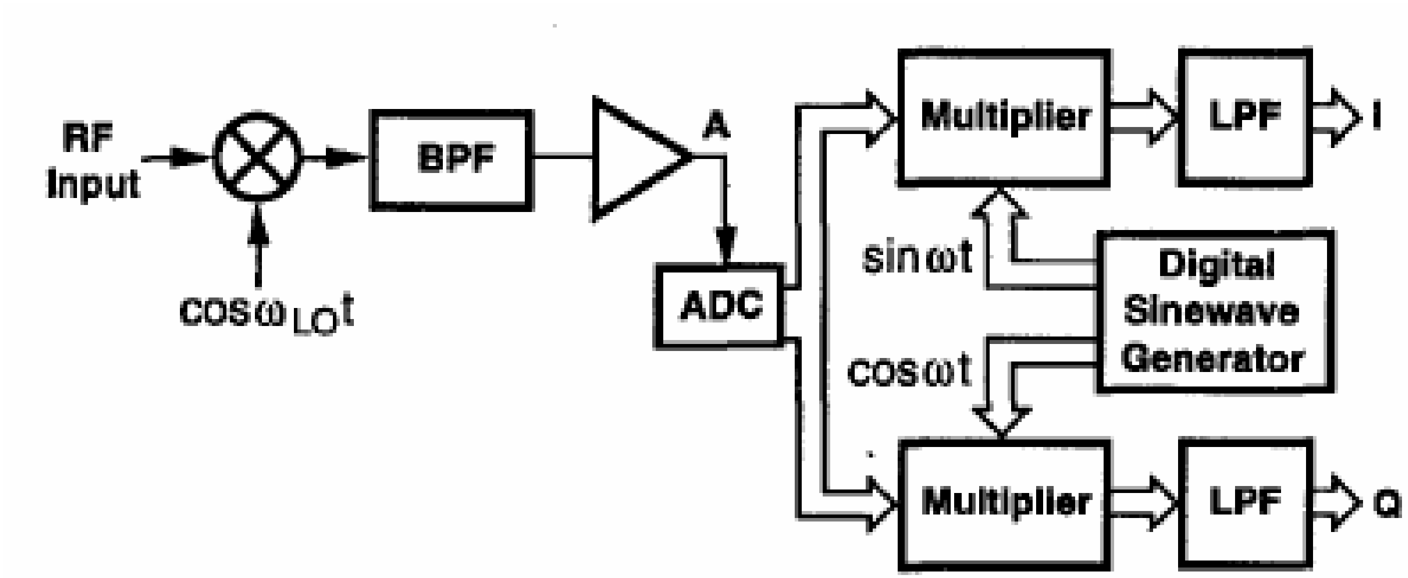


Image: B. Razavi

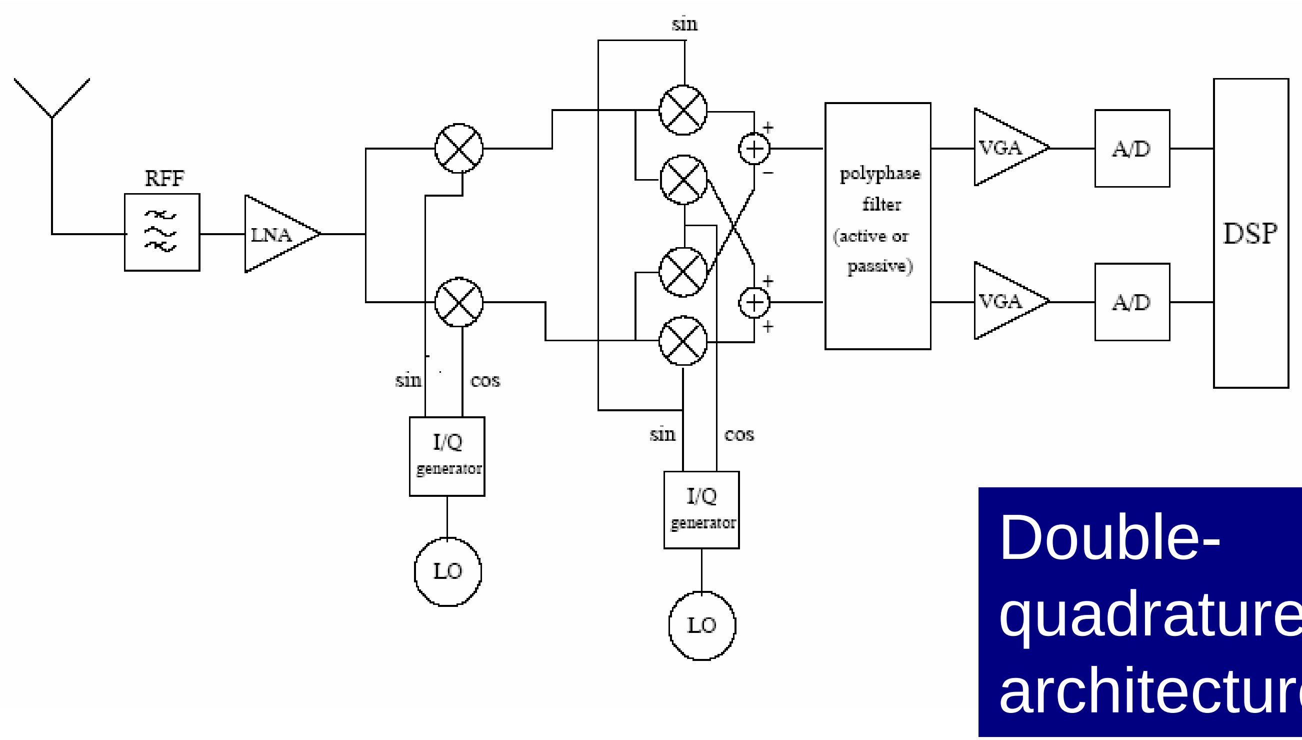
Received signal is digitized at the IF: high A/D requirements, but e.g. possible for FM radio.

Summary

- Key functions:
  - Selectivity (select wanted information)
  - gain (amplify weak received signa)
  - down-conversion (make filter feasible (acceptable Q) or ADC feasible)
- Down-conversion via mixer: image problem at 2IF away from RF
  - 1) suppress image at 2IF distance from RF via filter (high IF wanted!)
  - 2) mix with complex exponential (cos(ω_{LO}t) + jsin(ω_{LO}t)) (no exp(-ω_{Lo}t)!)
- Image filtering architectures:
  - Sub-sampling
  - Super heterodyne (traditional: amplify/filter at fixed IF)
  - Up-conversion
- Image rejection via mixing with complex exponential (quadrature)
  - Homodyne/Direct Conversion (simplest very popular)
  - Low-IF (low IF)
  - Digital IF
- Crucial operation: multiply by –j sgn(ω) (Hilbert transform: converts cosine to sine spectrum)

Examples of more advanced receiver architectures

Six-mixer Low-IF architecture



Double-quadrature architecture

Product of mismatch errors determines I/Q mismatch (?)

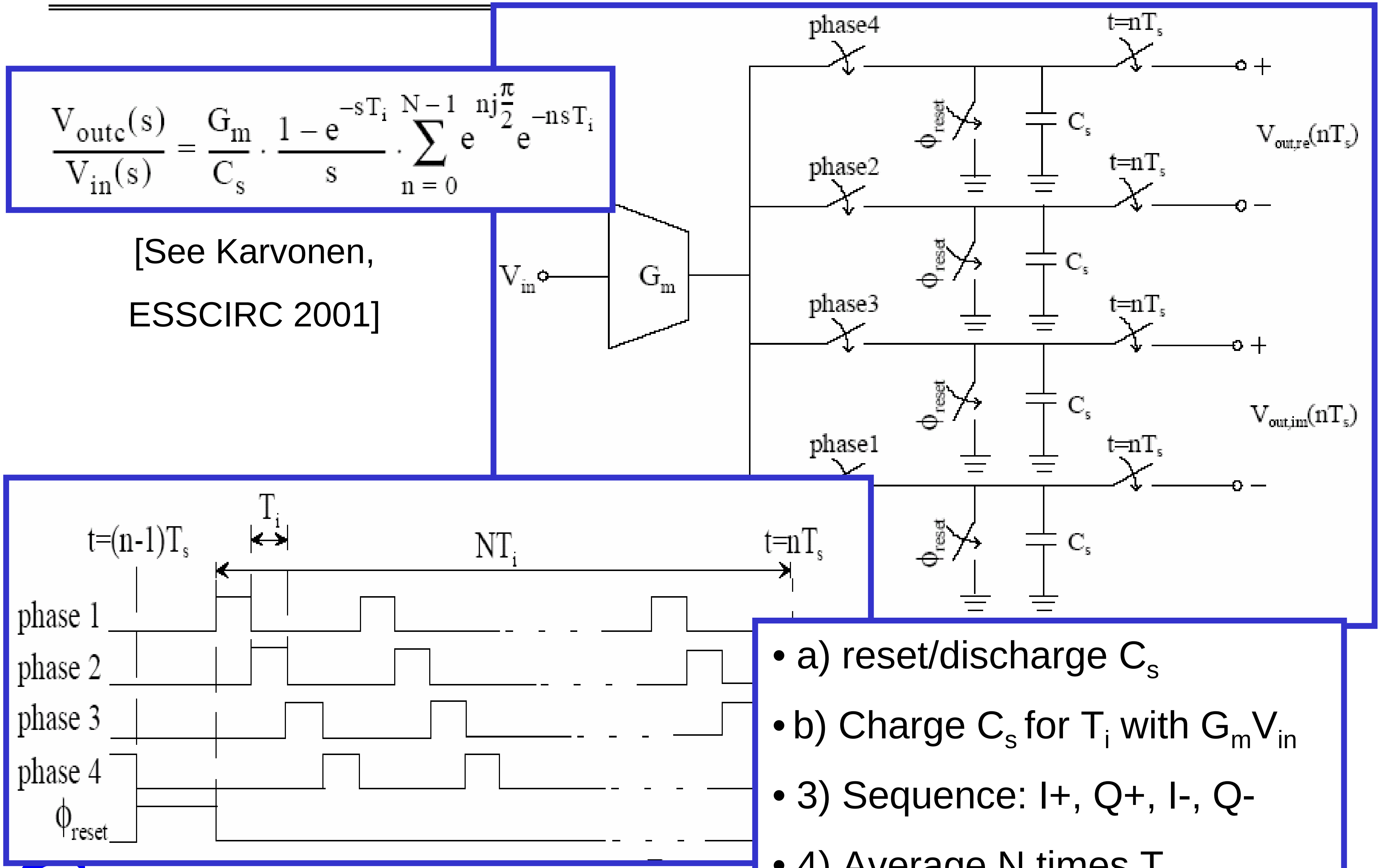
IRR can be significant higher than 40 dB become at the cost of more power dissipation and a higher complexity.

Example 1: Sub-sampled 4-phase IF-sampler

$$\frac{V_{outc}(s)}{V_{in}(s)} = \frac{G_m}{C_s} \cdot \frac{1 - e^{-sT_i}}{s} \cdot \sum_{n=0}^{N-1} e^{nj\frac{\pi}{2}} e^{-nsT_i}$$

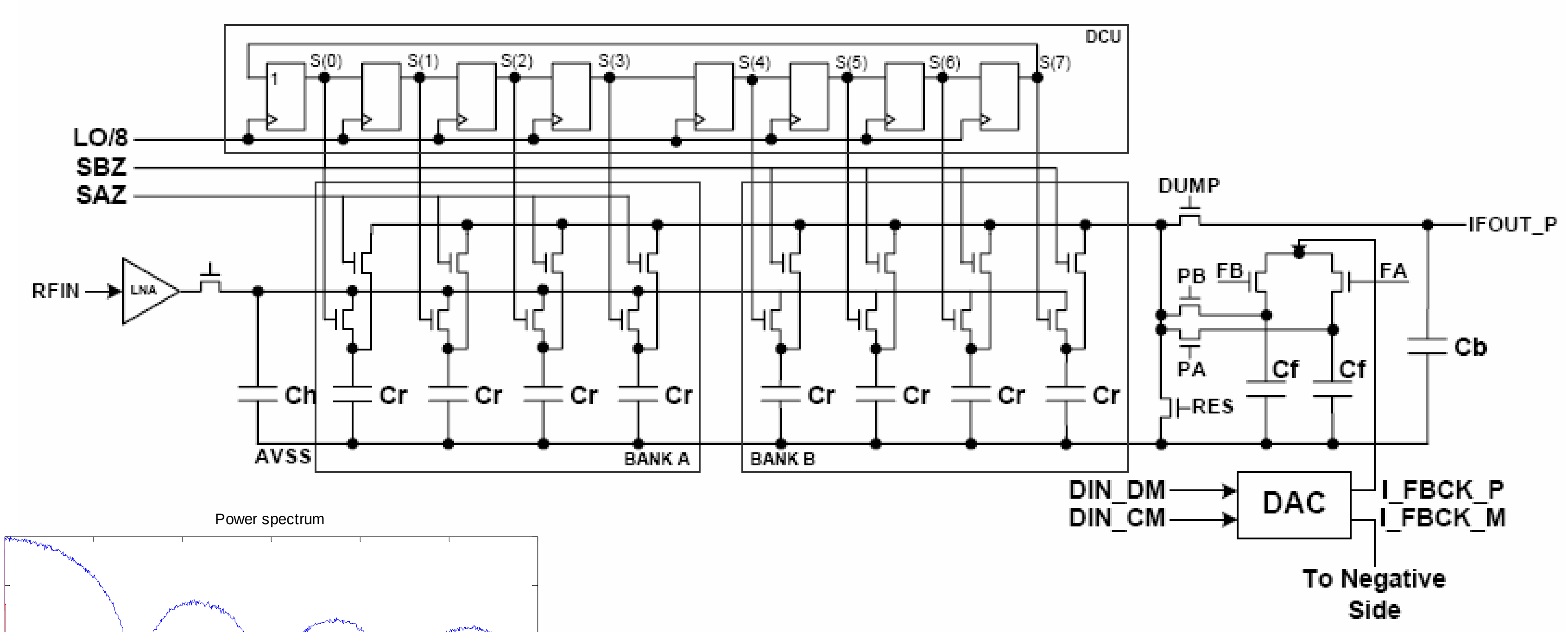
[See Karvonen,

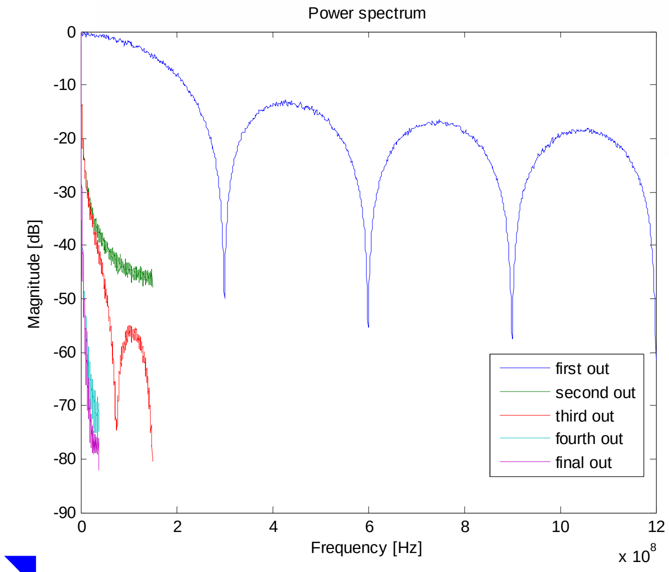
ESSCIRC 2001]



- a) reset/discharge C_s
- b) Charge C_s for T_i with G_mV_{in}
- 3) Sequence: I+, Q+, I-, Q-
- 4) Average N times T_i

Example 2: RF sampling receiver TI





Some properties (without explanation)

- Samples at $f_{LO}=f_{RF}$
- Time windowing: sync FIR filter
- Charge sharing Ch/Cr: IIR filtering

Key Papers On Receiver Architectures

Papers:

(Look-up with IEEExplore)

- B. Razavi: Architectures and circuits for RF CMOS receivers (overview of architectures)
- J.Crols & M. Steyaert: Low-IF topologies for high-performance analog front ends of fully integrated receivers (complex mixing, image rejection, polyphase filtering)