TSEK38: Radio Frequency Transceiver Design
Lecture 5: Low-IF

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Lecture schedule

w4:
- Le1: Introduction (Ch 1)
- Le2: Fundamentals of RF system modeling (Ch 2)
- Le3: Superheterodyne TRX design (Ch 3.1)

w6:
- Le4: Homodyne TRX design (Ch 3.2)
- Le5: Low-IF TRX design (Ch 3.3)
- Le6: Systematic synthesis (calculations) of RX (Ch 4)

w7:
- Le7: Systematic synthesis (continued)
- Le8: Systematic synthesis (calculations) of TX (Ch 5)

w8:
- Le9: Systematic synthesis (continued)

Lab schedule

w6:
- We: Lab1a (after Le6): 15-19 (ASGA)
- Th: Lab1b: 17-21 (SOUT)

w7:
- We: Lab1c (after Le8): 15-19 (SOUT)
- Th: Lab1d: 17-21 (EGYP)

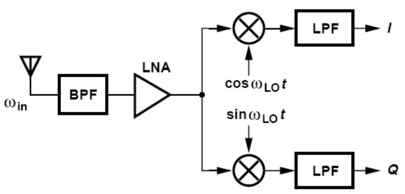
Instructions:
- One long lab (4 x 4 h).
- Lab manual in the Lisam *Course Documents/2019/Lab* folder.
- Supervision (Ted) available at the times above.
- To pass: complete and document the exercises in the lab manual, go through with Ted.

Repetion of Lecture 4

- Direct-Conversion (Zero-IF) Receivers
  - DC offset
  - IP2
  - IQ imbalance (cross-talk)
  - LO leakage
  - 1/f noise

Direct-Conversion (Zero-IF) Receivers

- Absence of an image greatly simplifies the design process.
- Channel selection is performed by on-chip low-pass filter.
- Mixing spurs are considerably reduced in number.
- Suitable for ICs, few external components.



Direct-Conversion (Zero-IF) Receivers

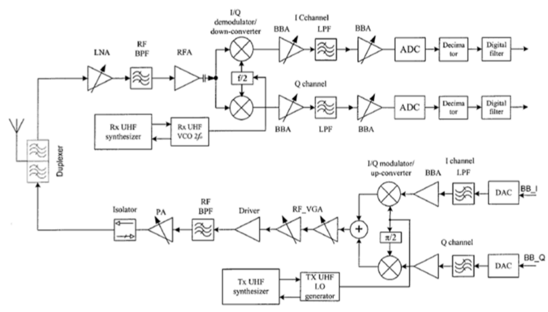


Figure 3.10. Block diagram of direct-conversion transceiver

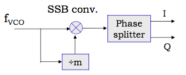
Frequency plan

RX synthesizer:

- operates at twice f_{RX} to generate IQ and avoid VCO pulling.
- If TX synthesizer is a separate chip the same technique can be used.

TX synthesizer:

- when integrated it should be designed to avoid VCO reverse modulation (2nd harmonic of TX can pull VCO at twice f_{TX}).
- Preferred is offset technique.



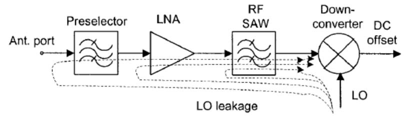
$$f_{LO} = (1 \pm \frac{1}{m}) f_{VCO}$$

3.2.2.1 DC offsets

A finite amount of in-band LO leakage appears at the LNA input. Along with the desired signal, this component is amplified and mixed with LO.

May saturate baseband circuits, simply prohibiting signal detection.

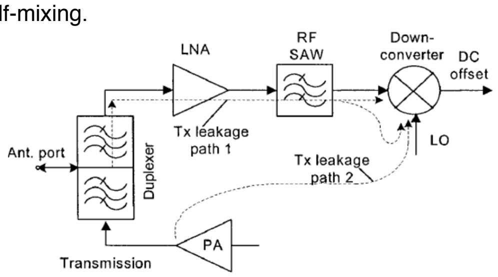
Also for the superheterodyne but much more severe with direct-conversion because of high BB gain (70-80 dB), so even a small offset (250 uV DC at the downconverter) can overload the ADC.



LO self-mixing

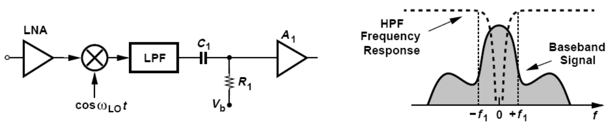
DC offsets

Another possible mixing problem: transmission leakage self-mixing.



DC offsets

- Cancellation: AC coupling, high-pass filters.
- Will also remove a fraction of the signal's spectrum near zero frequency, introducing ISI (3.2.3.1).



- But corner frequency has to be very low (f_{BB}/1000) =>, C1 may be very large and not suitable for integration.
- Many other solutions (circuit, architectures, calibration) also exist for this problem.

DC offset cancellation (time variant)

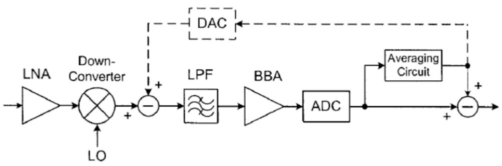


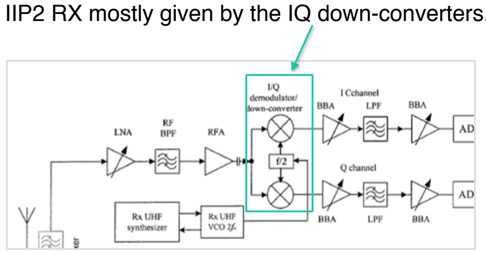
Figure 3.14. A possible configuration of DC offset cancellation

- Active DC offset cancellation by digital feedback, 4-6 bit DACs.
- Also 1/f noise partly reduced.

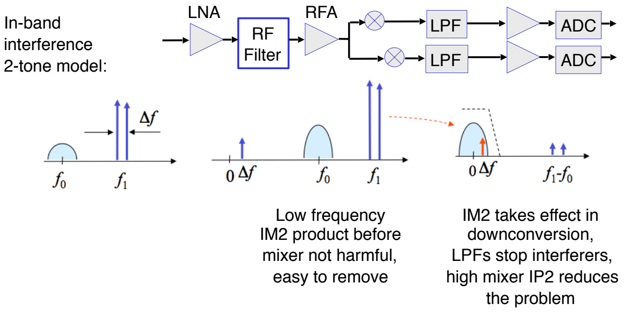
IP2 considerations (partially 3.2.3.2)

- High IIP2 is needed in direct-conversion receivers.
- 2nd order distortion by LNA and RFA easy to block with the RF BPF and AC coupling cap.

=> IIP2 RX mostly given by the IQ down-converters.



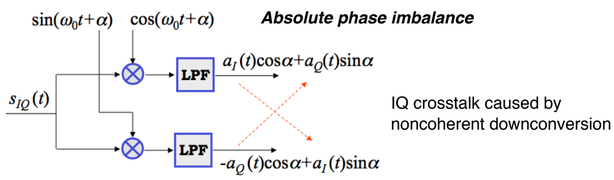
2nd order distortion



$\boxed{IM2_{RX} \approx IM2_{Mixer}}$ Homodyne RX needs very high IP2 of mixers

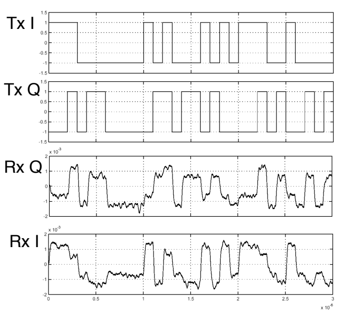
IQ mismatch (imbalance)

$s_{IQ}(t) = a_I(t)\cos\omega_0 t - a_Q(t)\sin\omega_0 t$

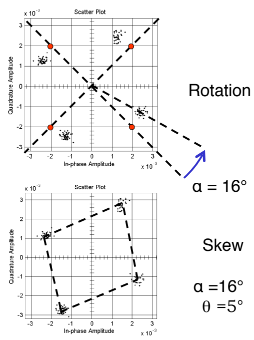


Complex envelope model for IQ downconversion: $\tilde{s}_{BB} = (a_I + ja_Q) \times (\cos\alpha - j\sin\alpha)$

QPSK simulation example: IQ crosstalk



Crosstalk for rotation α =16°

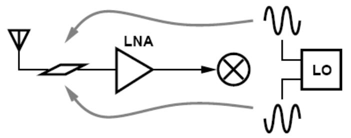


Received constellations

LO leakage emission

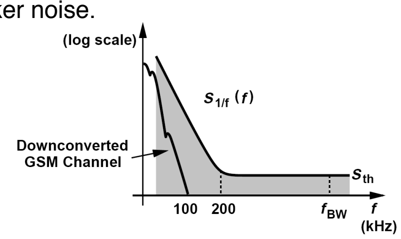
- Allowable emission level: -60 to -80 dBm
- LO input level to mixer: -5 to 0 dBm
- Reverse isolation to get < -80 dBm => > 85 dB
- LO leakage can be minimized through symmetric layout of the oscillator and the RF signal path.

=> LO leakage arises primarily from random or deterministic asymmetries in the circuits and the LO waveform.



Flicker noise

- Since the signal is centered around zero frequency, it can be substantially corrupted by flicker noise.



- Fix: lower 1/f noise, NF optimization of RX chain.

Summary

- Homodyne RX well suited for integration.
- Challenged by DC offset, high demands on IP2, 1/f noise.
- No image problem in RX.
- Most of the IP2-requirements are given by the down-conversion mixer,
- Homodyne TX simple – one step – but challenges by possible pulling of LO.

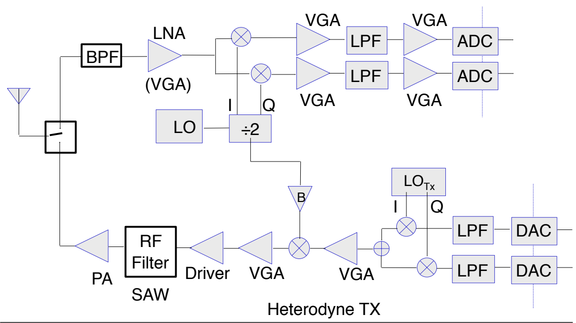
Outline of lecture 5

- Low-IF Architecture
  - Description (3.3.1.1)
  - Frequency plan
  - Close image problem
  - Effect of IQ imbalance (3.3.2.1)
  - Estimation of image rejection (3.3.3.2)
- Summary

Low-IF Receivers

- IF as low as 0.5 - 2x the signal BW.
- No DC offset problem.
- Possibly to select IF so that 2nd order intermixing (related to IP2) is outside the desired bandwidth.
- Reduces effect of 1/f noise.
- Good for narrowband standards (reduced 1/f noise).
- Main problem: Image rejection must still be considered. With low IF, it is hard to filter out images using a simple BPF without degrading sensitivity.
- No advantages for transmitters.

Low-IF architecture, half duplex
separate RX and TX bands



Low-IF architecture (advanced TDD)

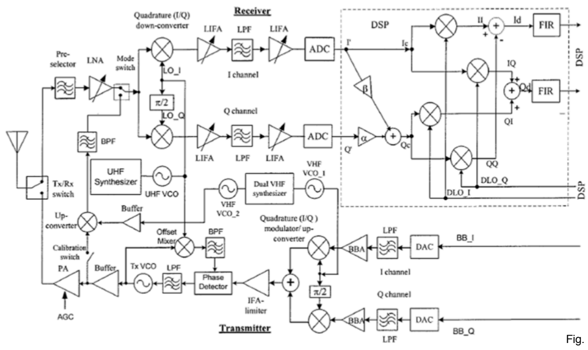


Fig. 3.21

Frequency plan

- TRX synthesizer operates at twice f_{RX} to avoid VCO pulling. Shared by RX and TX.

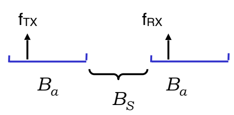
$$\boxed{f_{IF,Rx} = BW/2 = |f_{Rx} - f_{LO}|}$$

$$f_{Tx} = f_{LO} - f_{IF,Tx}$$

$$f_{Rx} = f_{Tx} + B_S + B_a$$

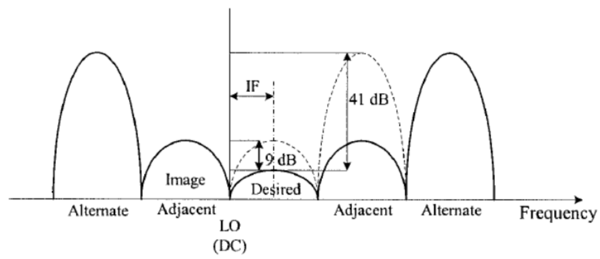
$$\Downarrow$$

$$f_{IF,Tx} = B_S + B_a \pm \frac{BW}{2}$$



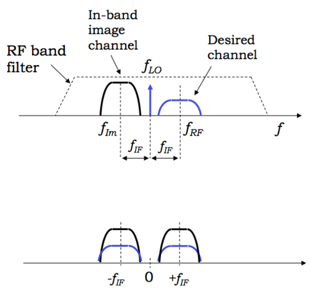
For GSM: IF_{TX} = 45MHz ±100kHz

Adjacent and Alternate Channels: definitions



Numbers for GSM

Close-image problem

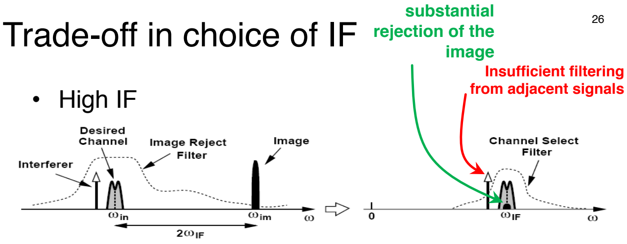


Tough requirements for IQ match if image is large, otherwise signal strongly corrupted

f_{IF} = ½ BW typical

Trade-off in choice of IF

- High IF



- Low IF

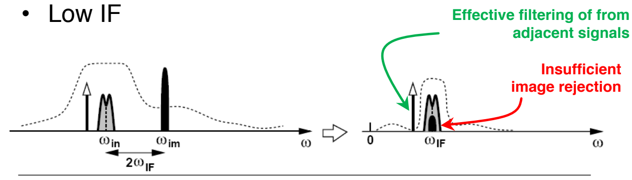
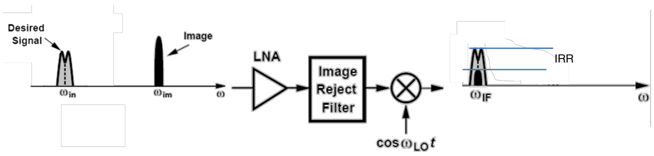


Image Rejection Ratio

- Image Rejection Ratio, IRR = (Power of the received signal)/(Power of the image signal) at the IF port
- Since IRR is a ratio, it is often expressed in dB.

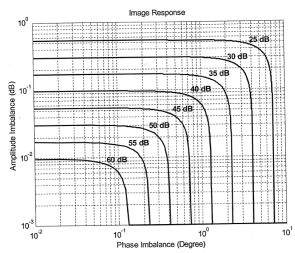


IQ imbalance and Image rejection (3.3.2.1)

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

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

δ - amplitude (gain) imbalance
ε - phase imbalance



IR is partly insensitive,
e.g. for 0.3d B gain imbalance, IR=30dB
keeps up to 2° phase imbalance

High IRR

- 3.3.2.2 Calibration of IQ (analog) in the RX + Digital Dual Quadrature Down-Converter Approach (baseband) (Fig. 3.21),
- complicated,
- IRR > 50 dB,
- can not be used with Full-Duplex.

- 3.3.2.2(again !) (analog) No calibration + Polyphase Band-Pass Filter Approach (directly after the mixer),
- power hungry,
- IRR > 40 dB.

Summary

- Low-IF RX is a tradeoff between heterodyne and homodyne.
- Blocking profile dictates IF = BW/2.
- DC offset and 1/f noise issues are reduced but close-in image is introduced.
- Image rejection in Low-IF RX more challenging than in homodyne RX.
- IQ correction and IR convenient after ADC.
- Good for narrow-band standards like GSM.

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