TSEK38: Radio Frequency Transceiver Design
Lecture 4: Homodyne TRX design

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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:
- $\boxed{\text{Le4: Homodyne TRX design (Ch 3.2)}}$
- 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)

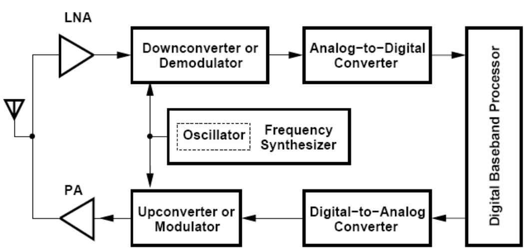
w7:
- We: Lab1c (after Le8): 15-19 (SOUT)
- Th: Lab1d: 17-21 (EGYP)

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.

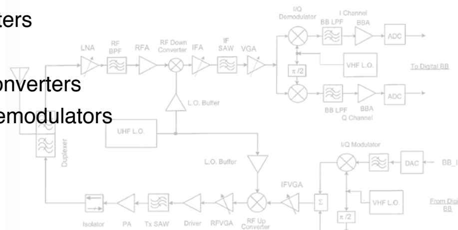
Repetion of Lecture 3

- Introduction RF TRX architectures
- Superheterodyne architecture
- Frequency planning
  - IF selection
  - Spurious analysis
- Design Considerations
- Summary

Generic RF Transceiver



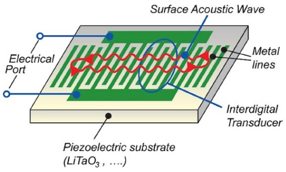
RF transceivers main building blocks



- frequency filters
- amplifiers
- frequency converters
- modulator/demodulators
- oscillators
- synthesizers
- ADC/DAC
- signal coupler/divider/combiner/attenuators
- switches
- power/voltage detectors
- …

The SAW filter

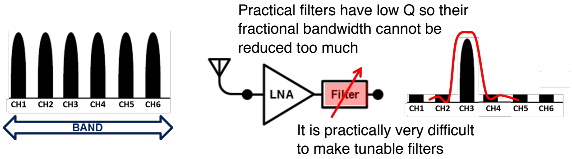
- SAW (surface acoustic wave) filters are electromechanical devices commonly used in radio frequency applications.
- Electrical signals are converted to a mechanical wave in a device constructed of a piezoelectric crystal or ceramic; this wave is delayed as it propagates across the device, before being converted back to an electrical signal by further electrodes. The delayed outputs are recombined to produce a direct analog implementation of a finite impulse response filter.
- This hybrid filtering technique is also found in analog sampled filters.
- SAW filters are limited to frequencies up to 3 GHz.



[Wikipedia]

Channel Selection

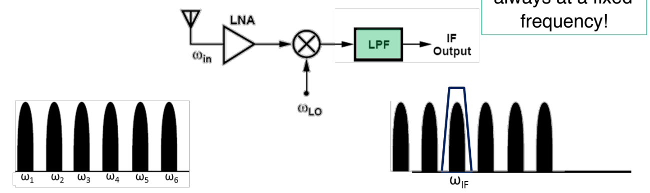
- Most communication systems divide the frequency band into several narrower channels.
- The receiver should select each channel for detection
  - Need for very sharp filter response (high Q-filter),
  - Need for variable filter (tunable filter).



Heterodyne Receiver – Channel Selection

- By changing ω_{LO}, different ω_{in} will down-convert to the same IF.

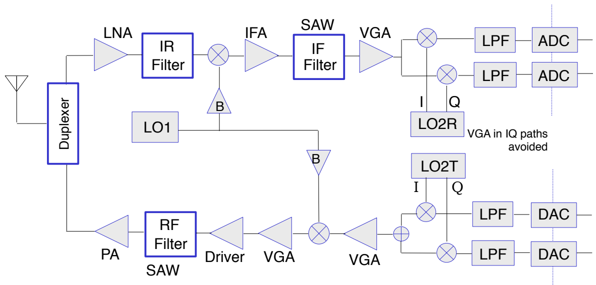
The IF filter is always at a fixed frequency!



Variable LO frequencies can be made with a synthesizer

$\omega_{LO1} = \omega_1 - \omega_{IF}$
$\omega_{LO2} = \omega_2 - \omega_{IF}$
$\omega_{LO3} = \omega_3 - \omega_{IF}$

Superheterodyne with analog IF architecture FDD, one antenna, shared LO1

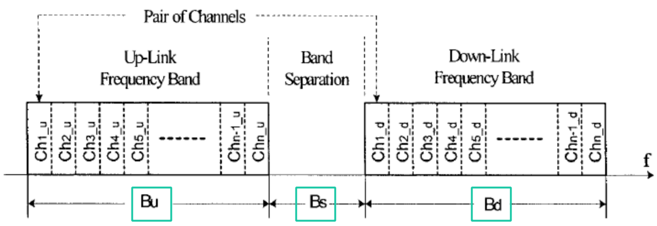


RF, IF filters and duplexer not integrated → matching issues.

Most of gain at IF (75 %) and RF. IF gain is more power efficient

Tx and Rx bands and IF

- Down-link (DL/forward link, to basestation/BS) and Up-link (UL/reverse link, mobile terminals/user equipment/UE) frequency band and channelization.



center frequency spacing = Bu + Bs = Bd + Bs if Bu = Bd (commonly true)
Ba = Bu = Bd

Frequency band allocation

Table 3.1. Frequency band allocations of wireless communication systems

Frequency Band/System	Up-Link Frequency Band (MHz)	Down-Link Frequency Band (MHz)	Band Separation (MHz)	Channel Spacing (kHz)	
Cellular	824 – 849	869 – 894	20	30 (CDMA)	
GSM 900	890 – 915	935 – 960	20	200	
E-GSM 900	880 – 915	925 – 960	10	200	
DCS 1800	1710 – 1785	1805 – 1889	20	200	
PCS	1850 – 1910	1930 – 1990	20	50 (CDMA)	
WCDMA	1920 – 1980	2110 – 2170	130	200	
802.11b	2400 – 2484	2400 – 2484	—	13000	TDD
802.11a	5150 – 5350 5725 – 5825	5150 – 5350 5725 – 5825	— —	20000 20000	TDD

Frequencies in a heterodyne TRX

- LO (UHF)
- reference oscillator
- 2 or more LO signals (VHF)
- 2 or more IF signals
- RF reception signal (weak)
- RF transmission signal (strong)

+ mixing product and harmonics

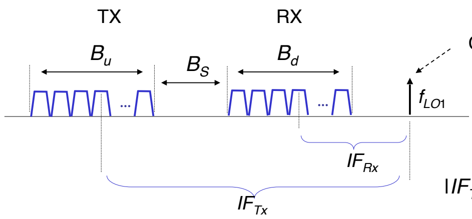
=> IF must be carefully chosen!

3.1.2.1 Criteria for IF selection, full duplex

1. If sharing LO for TX and RX: TX and RX will get different IF!

- Receiver: high selectivity IF BPF (SAW) is used.
- Transmitter: not so critical, SAW not necessary.

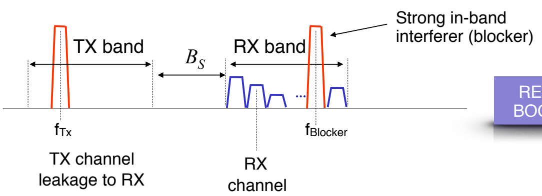
READ BOOK!



$B_u = B_d = B_a$

$|IF_{TX} - IF_{RX}| = B_a + B_S$

2. TX leakage and RX in-band jamming



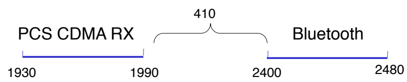
READ BOOK!

TX leakage through duplexer can be mixed with the blocker in Rx and fall in the IF band.
To prevent in-band jamming: $f_{TX} - f_{Blocker} \neq IF_{RX}$.
In practice: $IF_{RX} > 2B_a + B_S$ or $IF_{RX} < B_S$.

5. Multiband TRX constraints

READ BOOK!

- Another system should not be an image



$IF_{RX} < 205$ MHz

- Sharing LO1 by different systems with common IF_{RX} (frequency division by 2)

Cellular CDMA RX: 869… 894	$f_{LO1} = 2\times(869+IF_{RX})\ldots 2\times(894+IF_{RX})$
PCS CDMA: 1930… 1990	$f_{LO1} = (1930+IF_{RX})\ldots (1990+IF_{RX})$

LO1 tuning range: $\Delta f = Max\{2\times(894+IF_{RX}), (1990+IF_{RX})\}$
$- Min\{2\times(869+IF_{RX}), (1930+IF_{RX})\}$

3.1.2.2 Frequency planning, spurious analysis

$f_{Sp} = m\times f_A \pm n\times f_B$ of any two strong signals, esp. TX, TX IF, LO, etc.

$m, n = 1,2,3,4, \ldots$

$f_{har} = m\times f_A$ Also harmonics of LO2, LO3, IF_{TX}, and f_{ref}

Preferably spurs should not fall in:

- RX band
- Image band
- IF/2 band
- TX band
- LO band
- Other bands to be protected, e.g. GPS

Consider up to 8-12x for RF signals, 14-20x for IF signals. Frequencies are easy to predict, levels not.

Summary, Heterodyne Architecture

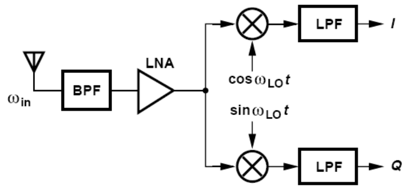
- Careful frequency planning required (IF frequencies).
- Many possible intermodulation effects must be considered.
- Pulling of LO by TX avoided (cf. Homedyne)
- Trade-off between sensitivity and selectivity in RX reduced by 2nd stage.
- LO in first stage can be shared, giving different IF_{TX} and IF_{RX}.
- Trade-off between sensitivity and linearity and power in RX.
- Most of RX gain at IF or BB (after removing blockers).

Outline of lecture 4

- Homodyne Architecture (3.2, 3.2.1)
- Challenges
  - – DC offset cancellation (3.2.2.1)
  - – Second order nonlinearity and IP2 (3.2.2.2)
  - – IQ imbalance (3.2.2.3)
  - – LO leakage emission (3.2.2.4)
  - – Flicker noise (3.2.2.5)
- 3.2.3 Design consideration
- 3.2.3.6 Direct-Conversion Transmitter
- Summary

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.



3.2.1 Direct Conversion configuration

- Section 3.2.1 (pp. 143-146) in the book gives many details on the direct-conversion transceiver building block functions and design selections.

READ BOOK!

Direct-Conversion (Zero-IF) Receivers

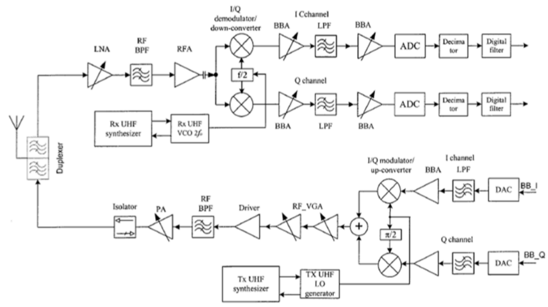


Figure 3.10. Block diagram of direct-conversion transceiver

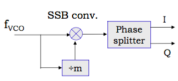
Frequency plan

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.

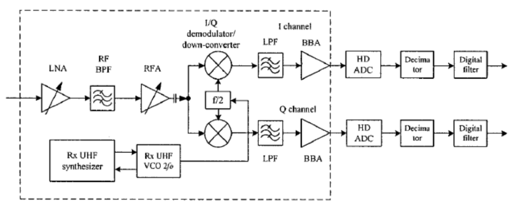
TX synthesizer:

- 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.



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

Direct conversion with high-dynamic ADCs



- 10-12 bits ADC.
- All gain control in the RF.
- Less IQ mismatch and DC offsets, if RF + filter well-designed.

Technical challenges

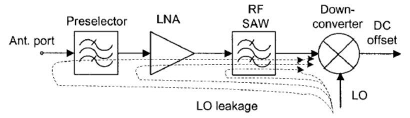
- Direct downconversion architecture introduced 1924, but not practically applied until 1980s for pagers, and mobile phones in the mid-1990s.
- Challenges:
  - DC Offsets (3.2.2.1)
  - Second-order distortion (3.2.2.2)
  - IQ mismatch (imbalance)
  - LO leakage
  - Flicker noise

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.

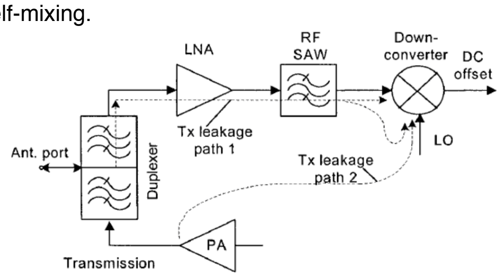
Also for the superheterodyne but much more severe with direct-conversion because of high BB gain (70-80 dB), so even a small offset (250 uV DC at the downconverter) can saturate the BB amp.



LO self-mixing

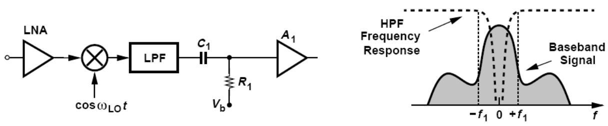
DC offsets

Another possible mixing problem: transmission leakage self-mixing.



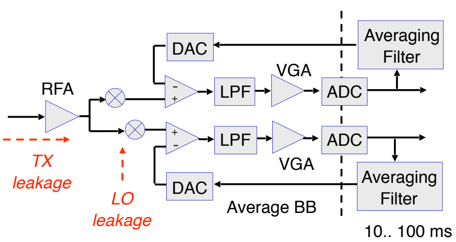
DC offsets

- 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)



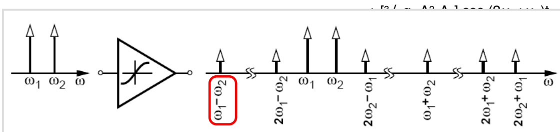
- Active DC offset cancellation by digital feedback, 4-6 bit DACs.
- Also 1/f noise partly reduced.

3.2.2.2 2nd order distortion

- Strong interferers and/or AM-modulated interferers => low-frequency in-channel interference.

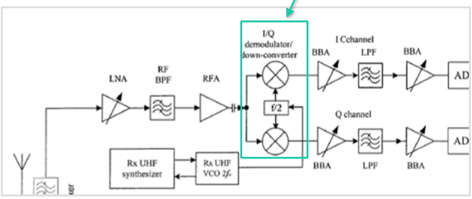
$A_1 \cos \omega_1 t + A_2 \cos \omega_2 t$

$$
\begin{aligned}
&\alpha_1(A_1 \cos \omega_1 t + A_2 \cos \omega_2 t) \\
&+ \alpha_2(A_1 \cos \omega_1 t + A_2 \cos \omega_2 t)^2 \\
&+ \alpha_3(A_1 \cos \omega_1 t + A_2 \cos \omega_2 t)^3 \\
&= \tfrac{1}{2}\alpha_2 (A^2_1 + A^2_2) \\
&+ [\alpha_1 + \tfrac{3}{4}\alpha_3 A^2_1 + \tfrac{3}{2}\alpha_3 A^2_2]\, A_1 \cos\omega_1 t \\
&+ [\alpha_1 + \tfrac{3}{4}\alpha_3 A^2_2 + \tfrac{3}{2}\alpha_3 A^2_1]\, A_2 \cos\omega_2 t \\
&+ [\alpha_2 A_1 A_2] \cos (\omega_1 \pm \omega_2) t \\
&+ [\tfrac{1}{2}\alpha_2 A^2_1] \cos 2\omega_1 t \\
&+ [\tfrac{1}{2}\alpha_2 A^2_2] \cos 2\omega_2 t \\
&+ [\tfrac{3}{4}\alpha_3 A^2_1 A_2] \cos (2\omega_1 + \omega_2) t
\end{aligned}
$$



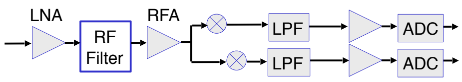
IP2 considerations (partially 3.2.3.2)

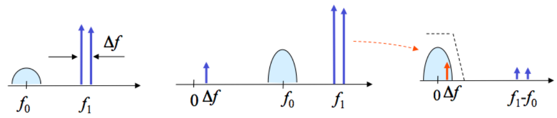
- High IIP2 is needed in direct-conversion receivers.
- 2nd order distortion by LNA and RFA easy to block with the RF BPF and AC coupling cap.
- => IIP2 RX mostly given by the IQ down-converters.



2nd order distortion

In-band interference 2-tone model:





Low frequency IM2 product before mixer not harmful, easy to remove

IM2 takes effect in downconversion, LPFs stop interferers, high mixer IP2 reduces the problem

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

3.2.2.3 IQ mismatch (imbalance)

- High BB gain (80 dB)
- I and Q separated on chip
- Wide range of gain control in both BB channels

=> Hard to keep I and Q perfectly symmetrical (gain and phase)

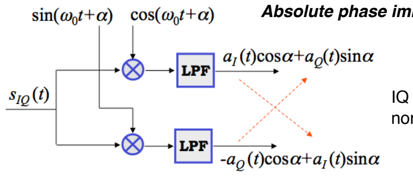
- Stepped gain control (3, 6, 9 dB) offers better accuracy than continuous gain control, but possibly DC-spikes during stepping.

- CDMA: <1 dB, <10° imbalance OK.
- Other standards: maybe 2x higher requirements.

IQ mismatch (imbalance)

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

Absolute phase imbalance



IQ crosstalk caused by noncoherent downconversion

Complex envelope model for IQ downconversion:

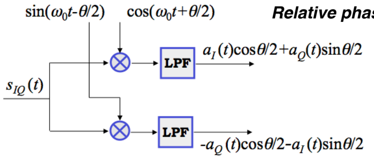
$\tilde{s}_{BB} = (a_I + ja_Q) \times (\cos\alpha - j\sin\alpha)$

IQ mismatch (imbalance)

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

(Also gain imbalance applies)

Relative phase imbalance

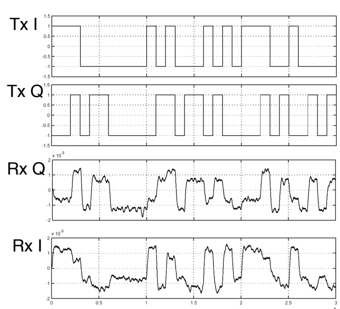


Also crosstalk but different effect on signal constellation

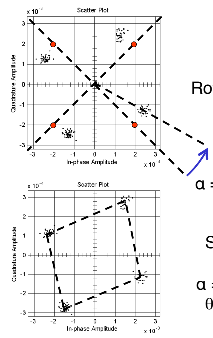
Complex envelope model for IQ downconversion:

$\Rightarrow \tilde{s}_{BB} = (a_I + ja_Q) \times (\cos\theta/2 + j\sin\theta/2)$

QPSK simulation example: IQ crosstalk



Crosstalk for rotation α =16°



Rotation

α = 16°

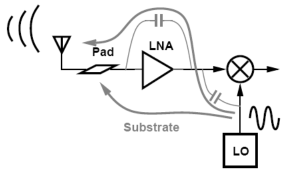
Skew

α =16°
θ =5°

Received constellations

3.2.2.4 LO leakage emission

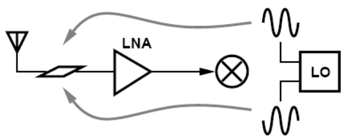
- LO couples to the antenna through:
  (a) device capacitances between LO and RF ports of mixer and device capacitances or resistances between the output and input of the LNA.
  (b) the substrate to the input pad, especially because the LO employs large on-chip spiral inductors.



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.



3.2.2.5 Flicker Noise

- Flicker noise or 1/f noise appears at low frequencies. It increases when frequency decreases.
- Flicker noise in MOSFET

$$\overline{V_n^2} = \frac{K}{WLC_{ox}} \frac{1}{f}$$

Transistor width Gate length

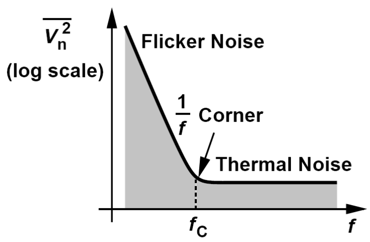
- *K* is a process dependent constant, which is typically lower for PMOS devices than NMOS transistors.

Flicker Noise: corner frequency

$$\overline{V_n^2} = \frac{K}{WLC_{ox}} \frac{1}{f}$$

$$\frac{K}{WLC_{ox}} \frac{1}{f_c} g_m^2 = 4kT\gamma g_m$$

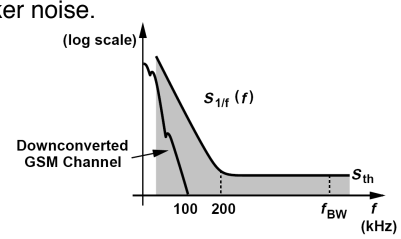
$$f_c = \frac{K}{WLC_{ox}} \frac{g_m}{4kT\gamma}$$



- For CMOS devices, the 1/f noise corner falls in the range of tens or hundreds of MHz in today's MOS technologies.

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.

3.2.3 Design consideration

- A lot of calculations
- We will be coming back to this in lectures 6 & 7.

3.2.3.6 Direct-Conversion Transmitter

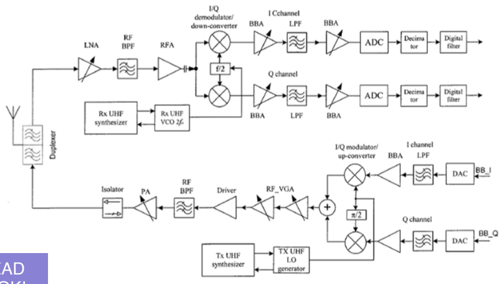


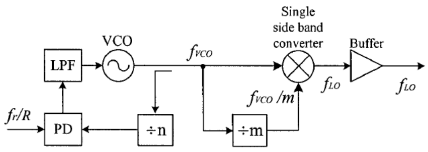
Figure 3.10. Block diagram of direct-conversion transceiver

READ BOOK!

Frequency plan

- **TX synthesizer:** when integrated, it should avoid VCO reverse modulation, since 2nd harmonic of TX can pull VCO at twice f_{TX}.
- Offset technique preferred.

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



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.

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