TSEK38: Radio Frequency Transceiver Design
Lecture 3: Superheterodyne 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)

w5:
- Le4: Homodyne TRX design (Ch 3.2)
- Le5: Low-IF TRX design (Ch 3.3)

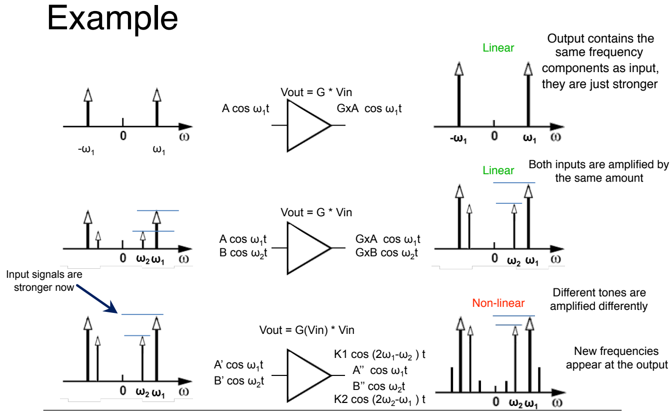
w6:
- Le6, Le7: Systematic synthesis (calculations) of RX (Ch 4)

w7-8:
- Le8, Le9: Systematic synthesis (calculations) of TX (Ch 5)

Repetion of Lecture 2

- Linear, Time-Invariant systems
- Linearity:
  - Harmonic distortion
  - Cross-modulation
  - Compression point
  - IP3
- Noise Figure
- Phase Noise

Example



Time Invariance

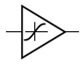
- Time-variant = response depends on the time of origin.
- A system is time-invariant if a time shift in its input results in the same time shift in its output.

  If $y(t) = f\,[x(t)]$

  then $y(t-\tau) = f\,[x(t-\tau)]$
- LTI: Linear time-invariant, $y(t-\tau) = L * [x(t-\tau)]$. A time shift in the input causes the same time shift in the output.
- Examples: filters, isolators, duplexers, linear amplifiers.

Effects of Nonlinearity

- Consider a nonlinear memoryless system

x(t)  $y(t) = \alpha_0 + \alpha_1 V_{in} + \alpha_2 V^2_{in} + \alpha_3 V^3_{in} + \ldots$

- Let us apply a single-tone ($A\cos\omega t$) to the input and calculate the output:

$$x(t) = A\cos\omega t$$

$$y(t) = \alpha_1 A\cos\omega t + \alpha_2 A^2\cos^2\omega t + \alpha_3 A^3\cos^3\omega t$$

$$= \frac{\alpha_2 A^2}{2} + \left(\alpha_1 A + \frac{3\alpha_3 A^3}{4}\right)\cos\omega t + \frac{\alpha_2 A^2}{2}\cos 2\omega t + \frac{\alpha_3 A^3}{4}\cos 3\omega t$$

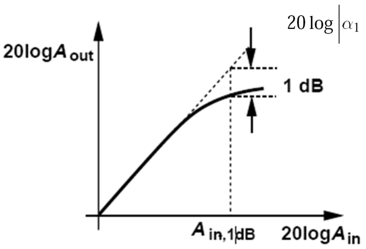
DC — Fundamental — Second Harmonic — Third Harmonic

Gain (1dB) Compression (p. 32)

- Eventually at large enough signal levels, output power does not follow the input power,

$$20\log\left|\alpha_1 + \frac{3}{4}\alpha_3 A_{in,1dB}^2\right| = 20\log|\alpha_1| - 1\text{ dB}.$$

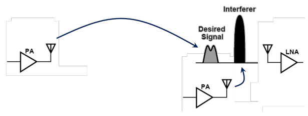
$$A_{in,1dB} = \sqrt{0.145\left|\frac{\alpha_1}{\alpha_3}\right|}.$$



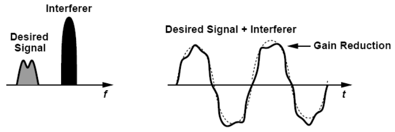
The P-1dB point correlates well to loss of linear behavior, getting out-of-spec in standards (EVM, ACPR, etc.) so for linear applications, operation beyond this point is useless.

Desensitization (p. 32)

- At the input of the receiver, a strong interference may exist close to the desired signal.



- The small signal is superimposed on the large signal (time domain). If the large signal compresses the amplifiers, it will also affect the small signal.

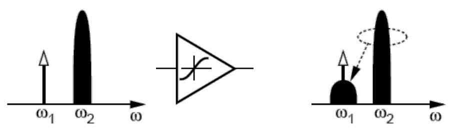


Cross-modulation (p. 32)

- Any amplitude variation (AM) of the strong interferer A_2 will also appear on the amplitude of the signal A_1 at the desired frequency and distort the signal.
- Interferer: $A_2(1 + m\cos\omega_m t)\cos\omega_2 t$ results in:

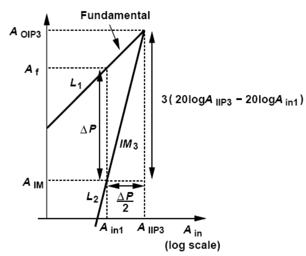
extra AM modulation occurs

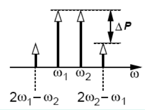
$$y(t) = \left[\alpha_1 + \frac{3}{2}\alpha_3 A_2^2\left(1 + \frac{m^2}{2} + \frac{m^2}{2}\cos 2\omega_m t + 2m\cos\omega_m t\right)\right]A_1\cos\omega_1 t + \cdots.$$



Intermodulation – Intercept Point

For a given input level (well below P1dB), the IIP3 can be calculated by halving the difference between the output fundamental and IM levels and adding the result to the input level, where all values are expressed as logarithmic quantities.

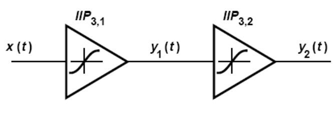




$$IIP_3|_{dBm} = \frac{\Delta P|_{dB}}{2} + P_{in}|_{dBm}$$

Cascaded Nonlinear Stages

- If each stage in a cascade has a gain greater than unity, the nonlinearity of the latter stages becomes increasingly more critical because the IP3 of each stage is equivalently scaled down by the total gain preceding that stage.



$$\frac{1}{IIP3_{total}} = \frac{1}{IIP3_A} + \frac{G_A}{IIP3_B} + \frac{G_A G_B}{IIP3_C}$$

Noise Figure/Factor

- Noise figure (factor) shows the noise performance of a system.

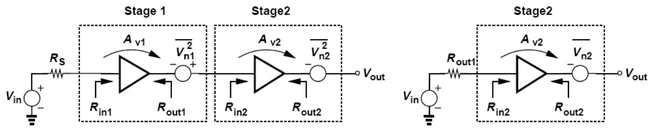
$$NF = \frac{SNR_{in}}{SNR_{out}}$$ Noise Factor

- It can be expressed in dB:

$$NF|_{dB} = 10\log\frac{SNR_{in}}{SNR_{out}}$$ Noise Figure

- NF depends on not only the noise of the circuit under consideration but the SNR provided by the preceding stage.
- If ideally a system adds no noise, F=1.
- If the input signal contains no noise, NF=∞.

Noise Figure of Cascaded Stages

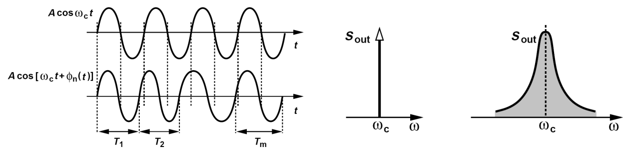


$$NF_{tot} = 1 + (NF_1 - 1) + \frac{NF_2 - 1}{A_{P1}} + \cdots + \frac{NF_m - 1}{A_{P1} \cdots A_{P(m-1)}}$$

Gain is power gain, which depends on the impedance of each stage.

Phase noise

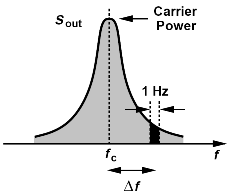
- The phase of the oscillator varies as Acos(ωc(t)+Φn(t)).
- The term Φn(t) is called the "phase noise."
- Can also be viewed as a random frequency variation, leading to a broadening of the spectrum called phase noise.



Phase noise

From TSEK03 RFIC, Razavi's book Ch. 8

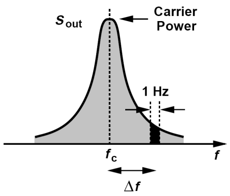
- Since the phase noise falls at frequencies farther from ω_c, it must be specified at a certain "frequency offset", i.e., at a certain difference with respect to ω_c.
- We consider a 1-Hz bandwidth of the spectrum at an offset of Δf, measure the power in this bandwidth, and normalize the result to the "carrier power", called "dB with respect to the carrier", **dBc**.



Example 8.23

From TSEK03 RFIC, Razavi's book Ch. 8

- At high carrier frequencies, it is difficult to measure the noise power in a 1-Hz bandwidth. Suppose a spectrum analyzer measures a noise power of -70 dBm in a 1-kHz bandwidth at 1-MHz offset. How much is the phase noise at this offset if the average oscillator output power is -2 dBm?



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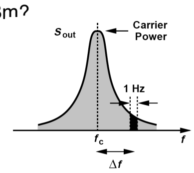
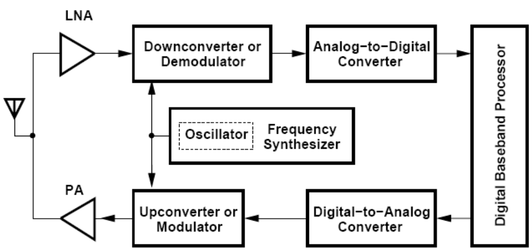


Since a 1-kHz bandwidth carries 10 log(1000 Hz) = 30 dB higher noise than a 1-Hz bandwidth, we conclude that the noise power in 1 Hz is equal to −100 dBm. Normalized to the carrier power, this value translates to a phase noise of −98 dBc/Hz.

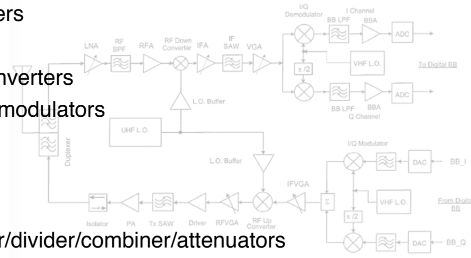
Outline of lecture 3

- Introduction RF TRX architectures (3)
- Superheterodyne architecture (3.1, 3.1.1)
- Frequency planning (3.1.2)
  - IF selection (3.1.2.1)
  - Spurious analysis (3.1.2.2)
- Design Considerations (3.1.3)
- Summary

Generic RF Transceiver



RF transceivers main building blocks

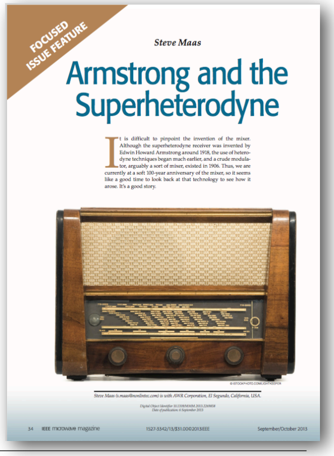


- frequency filters
- amplifiers
- frequency converters
- modulator/demodulators
- oscillators
- synthesizers
- ADC/DAC
- signal coupler/divider/combiner/attenuators
- switches
- power/voltage detectors
- …

Transceiver architectures

- Superheterodyne (Ch 3.1)
  - Most popular (and still is), invented in 1918.
  - Somewhat complex and limited flexibility by the fixed filters
- Homodyne (direct conversion, zero-IF)(Ch 3.2)
  - Integratabtle
  - Flexible
- Low IF (Ch 3.3) to overcome some drawbacks with the homodyne
- IF bandpass sampling (3.4), Software-defined radio, …

- Armstrong invented the superheterodyne in 1918.



S. Maas, IEEE Microwave Magazine, Sep/Oct 2013, p. 34

"Additional readings" folder

Quality Factor (Q)

- Quality factor of a filter is a quantitative measure of how much loss the filter exhibits
  - Lower quality factor indicates more losses
  - Practical filters (especially on-chip filters) have losses and therefore low Q
- It can be shown that the quality factor is inversely proportional to the fractional bandwidth of the filter:

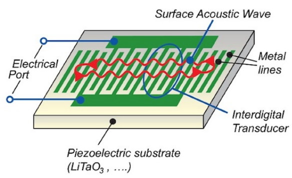
$\Delta f = BW / f_c$

f_c is the center frequency, BW is the -3 dB limit.

To have a small BW at high fc,
a filter with very high Q is needed

The SAW filter

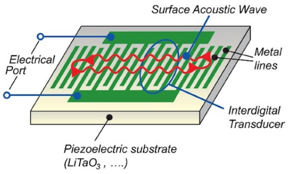
- SAW (surface acoustic wave) filters are electromechanical devices commonly used in radio frequency applications.
- Electrical signals are converted to a mechanical wave in a device constructed of a piezoelectric crystal or ceramic; this wave is delayed as it propagates across the device, before being 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]

The SAW filter

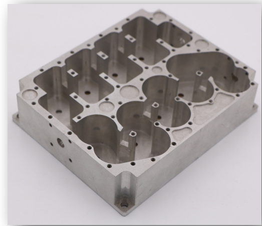
- SAW filters combine low insertion loss with good rejection, can achieve broad bandwidths and are a tiny fraction of the size of traditional cavity and even ceramic filters.
- Because SAW filters are fabricated on wafers, they can be created in large volumes at low cost.
- SAW technology also allows filters and duplexers for different bands to be integrated on a single chip with little or no additional fabrication steps.



[Wikipedia]

Cavity filters for basestations

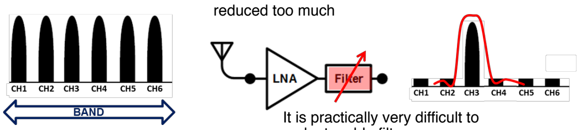
- Wikipedia: "Cavity filters are the basic circuitry behind a duplexer and are sharply tuned resonant circuit that allow only certain frequencies to pass.
- The Q of larger microwave cavities may exceed 10 000.
- Huge! Something like 40 x 70 x 15 cm.



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).

Practical filters have low Q so their fractional bandwidth cannot be reduced too much



It is practically very difficult to make tunable filters

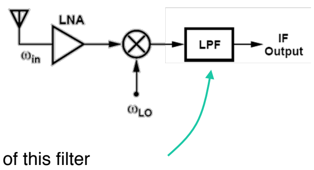
The problems of channel selection:

- Problem: We need to limit the bandwidth for better channel selection and limit the noise (improve the SNR).
- Solution: Reduce the center frequency, so that much lower BW can be achieved with the same fractional bandwidth.

- Problem: We need to filter signals at different frequencies (channels).
- Solution: Use a fixed filter and move the signal frequency instead.

Heterodyne Receiver – improved sensitivity

- By down-converting the radio-frequency signal (RF) to a lower intermediate frequency (IF), much better selectivity can be achieved and SNR is improved

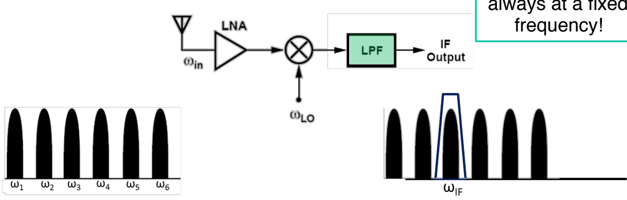


Bandwidth of this filter determines the noise power (kTB)

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!

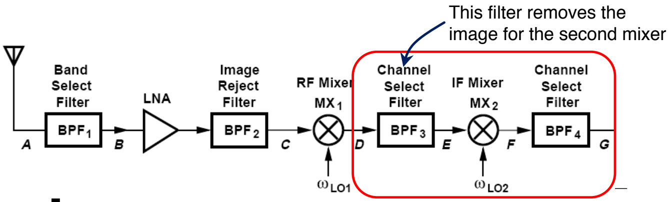


Variable LO frequencies can be made with a synthesizer

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

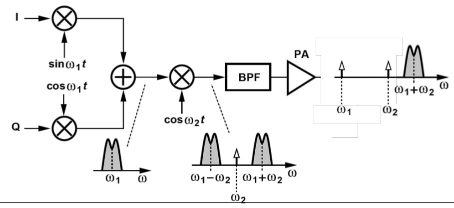
Dual Downconversion Architecture

- In order to avoid the problem of image and channel selectivity, down-conversion of the signal may be performed in two steps:
  - the image signal is removed in the first step (high IF)
  - in-band interference is removed in the second stage (low IF)



Two-step Conversion Transmitter

- In this architecture, we intentionally do not choose carrier frequency of the quadrature modulator to be the final transmission frequency, and perform a second frequency up-conversion by ω_2.
- We call ω_1 the intermediate frequency (IF).



3.1.1 Superheterodyne configuration

- Section 3.1.1 (pp. 115-119) in the book gives many details on the heterodyne building block functions and design selections.
- Highlights:
  - duplex/half-duplex, duplexer (FDD, TDD)
  - receiver RF, IF, BB
  - transmitter RF, IF, BB
  - transmitter PA classes

READ BOOK!

Superheterodyne, full-duplex TRX

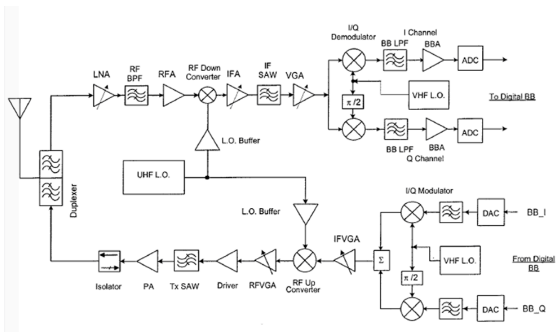
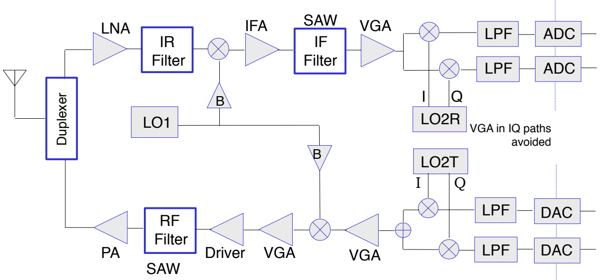


Fig 3.1, p. 116

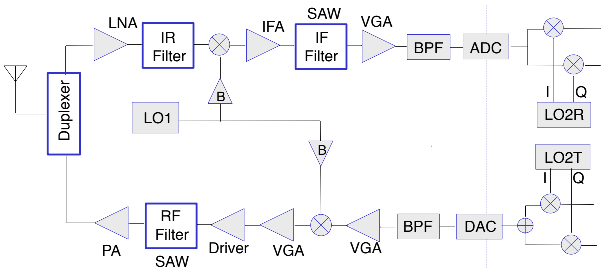
Superheterodyne with analog IF architecture FDD, one antenna, shared LO1



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

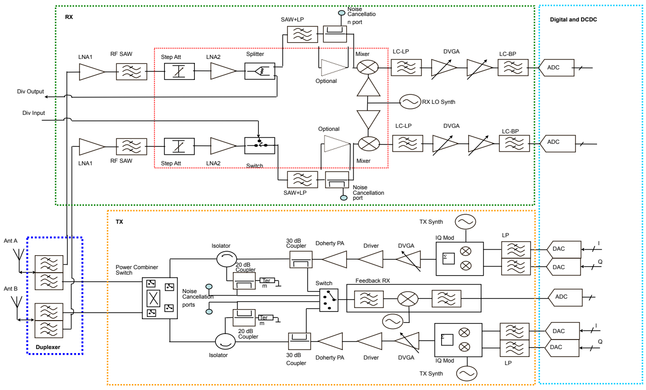
Most of gain at IF (75 %) and RF. IF gain is more power efficient

Digital IF Architecture FDD, one antenna, shared LO1



IQ mismatch avoided by digital IF but ADC/DAC need more power. ADC needs larger DR and must be more linear. Final filtering also digital.

Typical macrocell basestation architecture

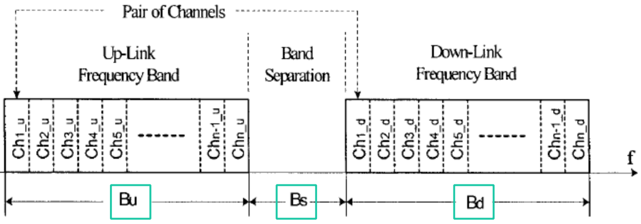


3.1.2 Frequency planning, IF selection

- Considerations:
  - Tx and Rx bands and IF
  - Tx leakage and Rx in-band jamming
  - IF/2 problem
  - Multiband TRX constraints

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

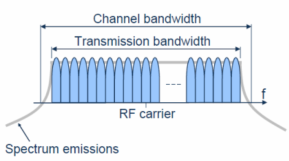
Frequency band allocation, 3GPP

E-UTRA Operating Band	Uplink (UL) operating band BS receive UE transmit F_{UL_low} – F_{UL_high}	Downlink (DL) operating band BS transmit UE receive F_{DL_low} – F_{DL_high}	Duplex Mode
1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz	FDD
2	1850 MHz – 1910 MHz	1930 MHz – 1990 MHz	FDD
3	1710 MHz – 1785 MHz	1805 MHz – 1880 MHz	FDD
4	1710 MHz – 1755 MHz	2110 MHz – 2155 MHz	FDD
5	824 MHz – 849 MHz	869 MHz – 894MHz	FDD
6	830 MHz – 840 MHz	875 MHz – 885 MHz	FDD
7	2500 MHz – 2570 MHz	2620 MHz – 2690 MHz	FDD
8	880 MHz – 915 MHz	925 MHz – 960 MHz	FDD
9	1749.9 MHz – 1784.9 MHz	1844.9 MHz – 1879.9 MHz	FDD
10	1710 MHz – 1770 MHz	2110 MHz – 2170 MHz	FDD
11	1427.9 MHz – 1452.9 MHz	1475.9 MHz – 1500.9 MHz	FDD
12	698 MHz – 716 MHz	728 MHz – 746 MHz	FDD
13	777 MHz – 787 MHz	746 MHz – 756 MHz	FDD
14	788 MHz – 798 MHz	758 MHz – 768 MHz	FDD
…			
17	704 MHz – 716 MHz	734 MHz – 746 MHz	FDD
...			
33	1900 MHz – 1920 MHz	1900 MHz – 1920 MHz	TDD
34	2010 MHz – 2025 MHz	2010 MHz – 2025 MHz	TDD
35	1850 MHz – 1910 MHz	1850 MHz – 1910 MHz	TDD
36	1930 MHz – 1990 MHz	1930 MHz – 1990 MHz	TDD
37	1910 MHz – 1930 MHz	1910 MHz – 1930 MHz	TDD
38	2570 MHz – 2620 MHz	2570 MHz – 2620 MHz	TDD
39	1880 MHz – 1920 MHz	1880 MHz – 1920 MHz	TDD
40	2300 MHz – 2400 MHz	2300 MHz – 2400 MHz	TDD

GSM, WCDMA, LTE
2.5G, 3G, 4G

Flexible spectrum in LTE

- 1.4 and 3 MHz are chosen to ease migration from CDMA2000/GSM/TD-SCDMA to LTE
- Transmission BW fill up 90% of channel BW (except 1.4MHz)



$BW_{channel}$ (MHz)	BW_{trans} (MHz)	BW_{Util}	N_{RB}	FFT size
1.4	1.08	77%	6	128
3	2.7	90%	15	256
5	4.5	90%	25	512
10	9.0	90%	50	1024
15	13.5	90%	75	1536
20	18.0	90%	100	2048

Frequencies in a heterodyne TRX

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

+ many mixing product and harmonics

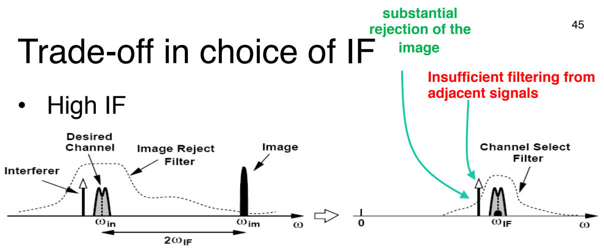
=> IF must be carefully chosen!

Choice of Intermediate Frequency

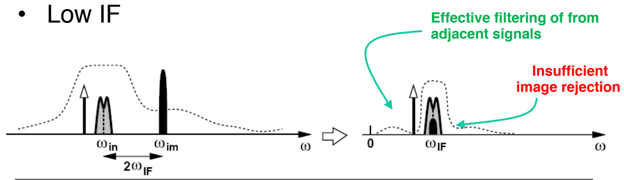
- By lowering the signal frequency to an intermediate frequency (IF), we can reduce the bandwidth and therefore improve the SNR.
- The lower we chose this intermediate frequency, the better performance we can get.
- What limits us from choosing very low IF?

Trade-off in choice of IF

- High IF



- Low IF



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.

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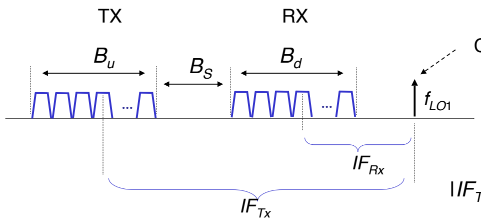
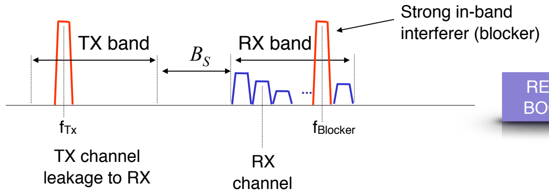


$B_u = B_d = B_a$

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

2. TX leakage and RX in-band jamming



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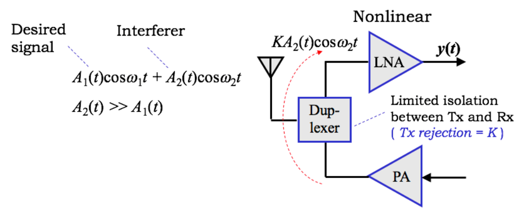
TX leakage through duplexer can be mixed with the blocker in Rx and fall in the IF band.
To prevent in-band jamming: $f_{TX} - f_{Blocker} \neq IF_{RX}$.
In practice: $IF_{RX} > 2B_a + B_S$ or $IF_{RX} < B_S$.

Reminder: *Cross-modulation example*



Typical for FDD transceivers with non-constant amplitude modulation, e.g. QAM

3. The IF/2 issue

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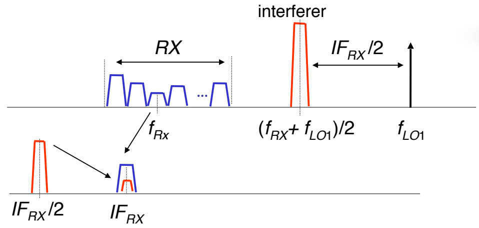

- Mixing of 2nd harmonics: $2 \times f_{LO1} - 2 \times (f_{RX} + f_{LO1})/2 = IF_{RX}$ (LO 50% duty cycle to avoid 2nd harmonic)
- Downconversion to $IF_{Rx}/2$ and subsequently 2nd order distortion – less harmful because of IF filter.
- IF/2 interferer must be suppressed: $IF_{RX}/2 >> B_a$

4. Multiband TRX constraints

- For multiband TRX, IF_{RX} must be max of the bands covered, while TX follows $IF_{TX} = IF_{RX} + B_a + B_S$.
- Same IF filters can be used unless channel BWs are very different.
- TX frequency can interfere with IF and fall in the RX band of another system on the same mobile platform:

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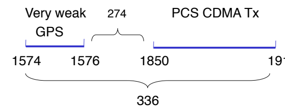
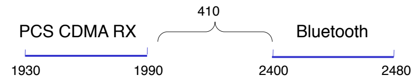


{ $IF_{TX} < 274$ MHz *or* $IF_{TX} > 336$ MHz} and $IF_{RX} = IF_{TX} - B_a - B_S = IF_{TX} - 80$MHz

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

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.

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

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

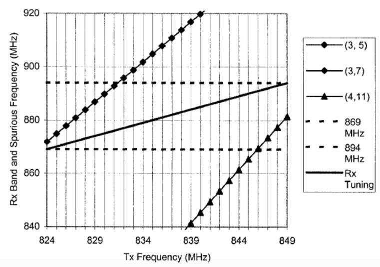
Preferably spurs should not fall in:

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

Example: Cellular CDMA TRX (full-duplex)

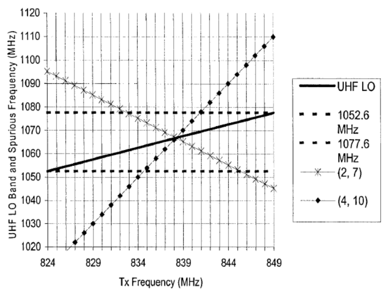
$IF_{RX} = 183.6$ MHz
$IF_{TX} = IF_{RX}+B_a+B_S = 228.6$ MHz
$f_{Sp1} = 3f_{TX} - 7IF_{TX}$
$f_{Sp2} = 3f_{LO1} - 5f_{LO2}$

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)



Those spurious response lines do not intersect with the TRX tuning line. Should they do, then the RX signal would be corrupted. Here they are rather weak in-band interferers.

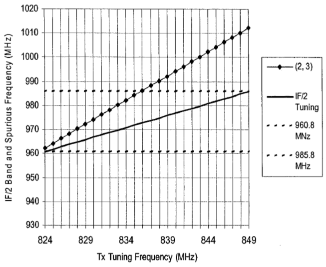
Example: Cellular CDMA TRX (full-duplex)



$f_{Sp3} = 7f_{LO3} - 2f_{LO1}$

This spurious response line coincides with the TRX tuning line.
The spur can mix with the RX signal to produce IF component, but it should not be harmful

Example: Cellular CDMA TRX (full-duplex)



$f_{IF/2} = (f_{RX}+f_{LO1})/2$
$= f_{TX}+B_a+B_S+IF_{RX}/2$
$f_{Sp4} = 2f_{TX} - 3IF_{TX}$

Does not interfere with the IF/2 band

Design considerations (pp. 133-142)

3.1.3.1 Receiver

- Trade-off between sensitivity and selectivity (filters).
- Trade-off between sensitivity, linearity, and power.
- SFDR is a joint measure of noise and linearity (IP3). Here instead Q = IIP3-NF. (3.1.10)
- Most of Rx gain at IF.
- Blocking determined by selectivity, phase noise, spurs of the synthesizer (IF and BB filters important), and linearity.

READ BOOK!

Design considerations

3.1.3.2 Transmitter

- Trade-off between power efficiency and spectral efficiency.
- Power, power tolerance and control, 2-3 dB back-off, PA linearization.
- Pulse shaping and filtering (to limit ACPR and spurious).
- Modulation accuracy (EVM, ρ, phase error).
- Effect of phase noise, filter group delay, and LO leakage.

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Design considerations

RX dynamic range

- RX signal range, in-band blocking.
- Best use of ADC, max RX gain.
- AGC needed (mainly at IF/BB), transient response constraints.

TX dynamic range

- CDMA systems need large DR ≈ 70dB (near-far effect)
- Other systems need much less DR ≈ 30dB
- Gain control mainly at IF for power savings

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Summary, Heterodyne Architecture

- Pulling of LO by TX avoided
- Careful frequency planning required (IF frequencies).
- Many possible intermodulation effects must be considered.
- 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).
- Today heterodyne architecture mostly for TX rather than for RX since IR filters difficult to integrate.

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