RF System Design

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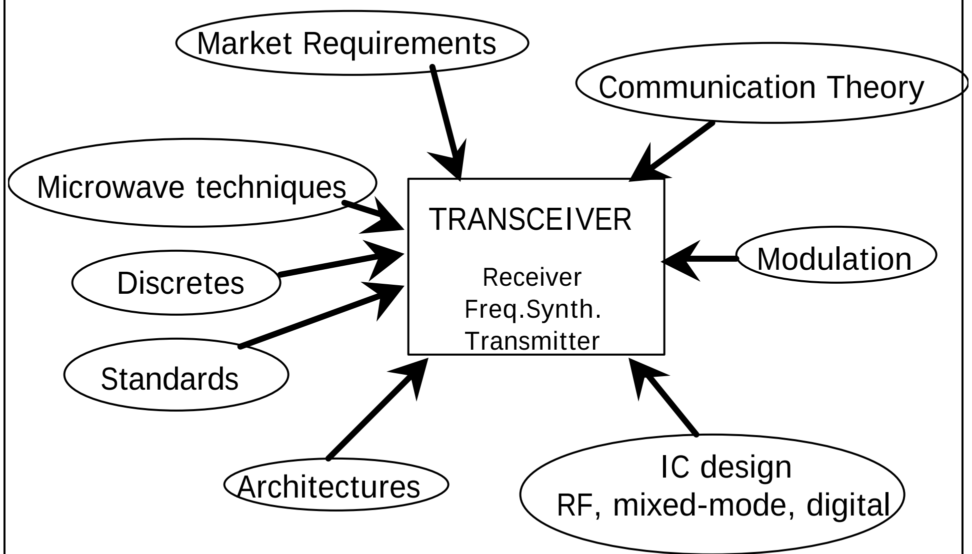
Outline

- Circuits for Wireless
- Wireless Communications
  - duplex, access, and cellular communication systems
  - standards
- Receivers:
  - heterodyne
  - homodyne
  - image reject
- Transmitters
  - modulation
  - up-conversion
- Transceivers
  - frequency synthesis
  - examples

RF IC design



Circuits for Wireless

Circuits for Wireless - Overview

- Noise limits the *smallest* signal
    - noise figure
    - cascade of stages
- Distortion limits the *largest* signal
    - large (interfering) signals:
        - compression, blocking, and desensitization
        - inter-modulation
        - cascade of stages
- Dynamic Range

Noise Figure

- Max. thermal noise power from linear passive network e.g. antenna: $N_{max} = kT \cdot BW$
- Noise Factor: $F = \frac{(S/N)_{in}}{(S/N)_{out}} = 1 + \frac{N^{added}_{eq@input}}{N_{in}}$
- Noise Figure: $NF = 10\log_{10}(F) \geq 0dB$

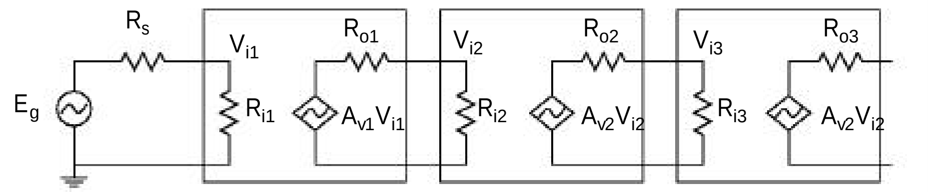
NF [dB]	F
0	1
1	1.25
2	1.6
3	2

$(S/N)_{out}$=1/2 $(S/N)_{in}$

Cascade of Stages: Friis Equation

Avail. Power Gain: A_{p1} A_{p2} A_{p3}

Noise factor: F_1 F_2 F_3

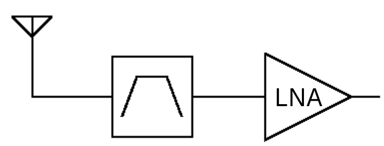


$$F = 1 + (F_1 - 1) + \frac{(F_2 - 1)}{A_{P1}} + \frac{(F_3 - 1)}{A_{P1} A_{P2}}$$

⇨ later blocks contribute less to the noise figure if they are preceded with gain

Noise of lossy passive circuit

- Lossy passive circuit (e.g. filter): $F = \text{Loss}$
- E.g. Band-select filter & LNA:



$$F = F_{filt} + \frac{(F_{LNA} - 1)}{A_P}$$

$$F = L + \frac{(F_{LNA} - 1)}{1/L} = L \cdot F_{LNA}$$

Loss adds immediately to noise figure !

Sensitivity

- sensitivity = minimal signal level that receiver can detect for a given (S/N) at the output:

$$F = \frac{(S/N)_{in}}{(S/N)_{out}} = \frac{P_{signal\_in}}{P_{noise\_in}} \cdot \frac{1}{(S/N)_{out}}$$

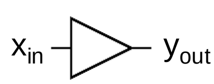
$$\boxed{\begin{aligned} P_{signal\_in} &= F \cdot (S/N)_{out} \cdot P_{noise\_in} \\ &= F \cdot (S/N)_{out} \cdot kT \cdot BW \end{aligned}}$$

- E.g. GSM (BW=200kHz, $(S/N)_{out}$ > 9dB):

$$\begin{aligned} P_{signal\_in} &= NF + (S/N)_{out} - 174 dBm/Hz + 10\log_{10}(BW) \\ &= 6 + 10 - 174 + 53 = -105 dBm \end{aligned}$$

for a receiver with a noise figure of 6dB

Distortion:

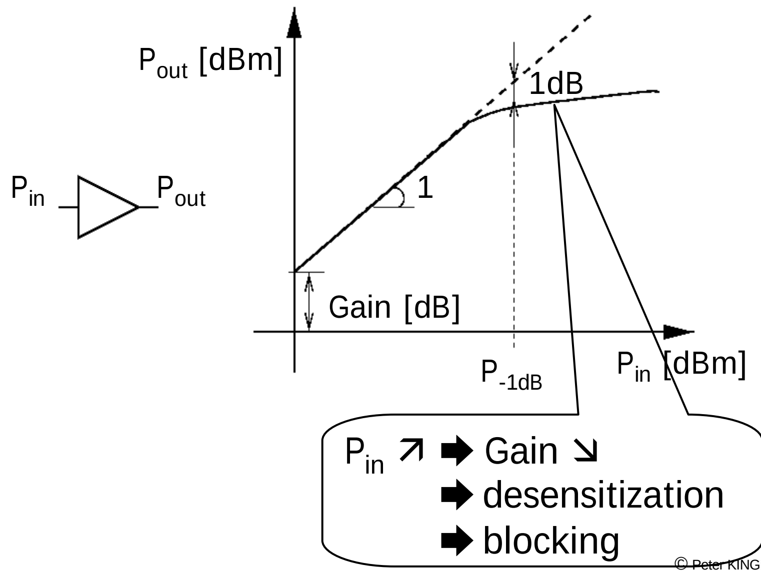


- Circuits have non-linearities
  - hard: e.g. supply clipping
  - weak: $y_{out} = G_1 \cdot x_{in} + G_2 \cdot x_{in}^2 + G_3 \cdot x_{in}^3 + \cdots$

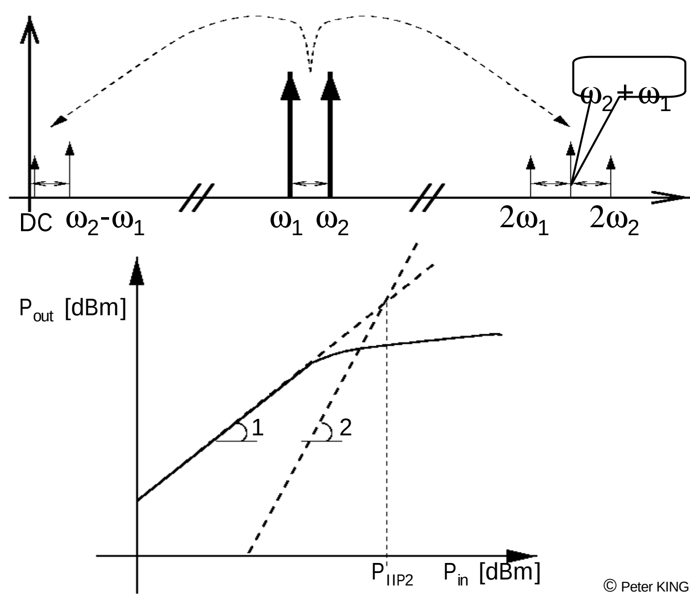
$$G_1 >> G_2 \;\&\; G_1 >> G_3$$

- Effects:
  - Gain compression
  - Blocking & Desensitization
  - Inter-modulation: IP2 & IP3
- Cascade of stages

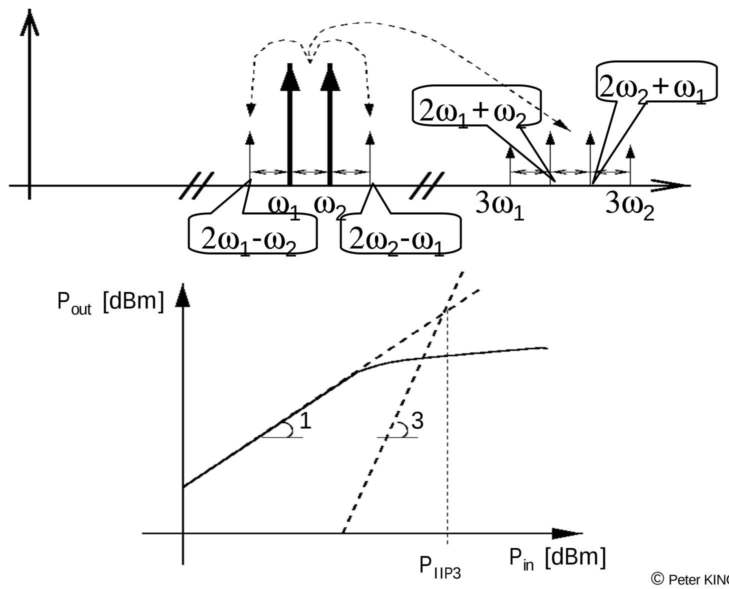
Gain Compression



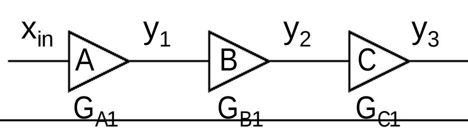
Inter-modulation: 2nd order



Inter-modulation: 3rd order



IIP_3 for a cascade of stages



$$\frac{1}{A_{IIP3}^2} \leq \frac{1}{A_{A\,IIP3}^2} + \frac{G_{A1}^2}{A_{B\,IIP3}^2} + \frac{G_{A1}^2 \cdot G_{B1}^2}{A_{C\,IIP3}^2}$$

- worst-case approximation for narrow band systems !
- voltage/current levels and gains
- effect of non-linearities more important at *later stages* !

Spurious Free Dynamic Range

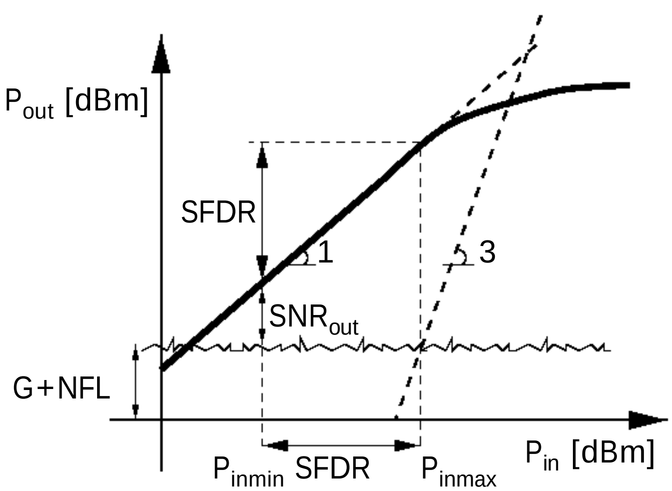
$$\text{dynamic range} = \frac{\text{max. input level}}{\text{min. input level}}$$

- under certain conditions:
  - min. level such that $(S/N)_{out}$ is sufficient
  - max. level such that:

    effects of non-linearities are ≤ noise

    i.e. IM3 products ≤ noise
- other applications use different conditions

Spurious Free Dynamic Range



Wireless Communication Systems

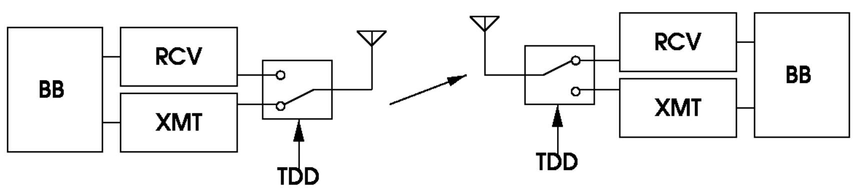
Wireless Communications - Overview

- 'ether' is one medium shared by all
- 1st problem: Duplexing
  - how to arrange for a two way communication link
- 2nd problem: Multiple Access
  - how to arrange for multiple users

Duplexing - Overview

- Establish two way communications:
  - Time division duplex:
    - same rcv and xmt frequency channel
    - alternating in time between rcv & xmt
  - Frequency division duplex
    - different frequency channel for rcv and xmt
    - full duplex possible

Time Division Duplex (TDD)



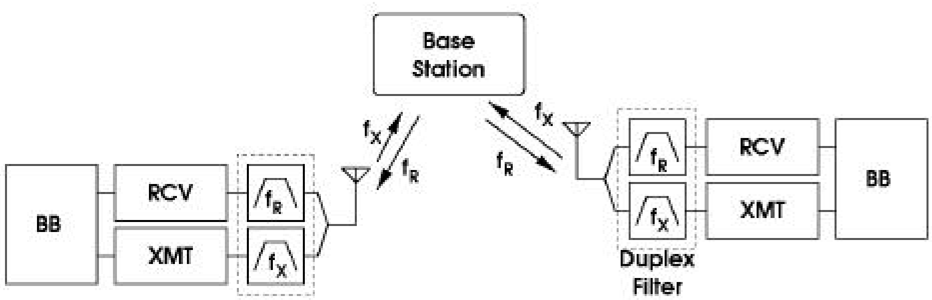
- peer to peer communications
- antenna switch

TDD design issues

+ mobile units can communicate
+ Switch low loss (<1dB)
+ XMT cannot desensitize RCV
- nearby XMT can overload RCV
+ channel leakage from P/A reduction by proper timing

• packet based communication:
  – Synchronization & Buffering needed
  – digital implementation

Frequency Division Duplex (FDD)



• base station <> mobile unit
• no peer to peer communication
• duplex filter

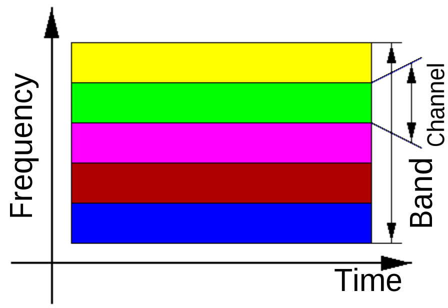
FDD design issues

– duplexer loss (2~3dB)
  – adds directly to noise figure
  – reduces XMT efficiency
– duplexer isolation < ~50dB
  – still desensitization of RCV by XMT possible
+ less sensitive to nearby XMT
– direct XMT antenna connection
  – LO transients or P/A switch results in channel leakage
+ analog implementation

Multiple Access - Overview

- Frequency Division Multiple Access (FDMA)
  – divide band in channels & allocate *different channel* for each user
- Time Division Multiple Access (TDMA)
  – same channel for different users but each user accesses in a *different time-slot*
- Code Division Multiple Access (CDMA)
  – all users use same channel at same time but have a *different code*
- Carrier Sense Multiple Access (CSMA)
  – all users use same channel at *different (random) times*

Frequency Division MA (FDMA)

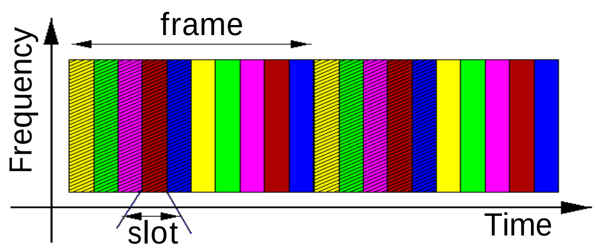


- each user is assigned a channel
- FDD & FDMA ➨ xmt & rcv channel

\+ implementation can be done analog

– you need high quality filters (loss….)

Time Division Multiple Access (TDMA)



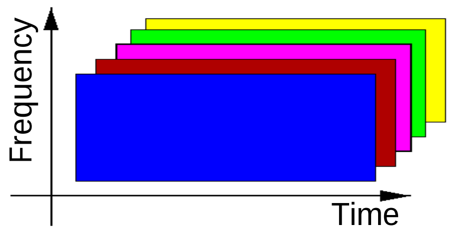
- each user is assigned a slot

– synchronization & data buffering ➨ digital

\+ add coding, correction, compression ➨ capacity ⇑

\+ FDD & TDMA:
time RCV & XMT non-simultaneous
➨ advantages of TDD

Code Division Multiple Access (CDMA)

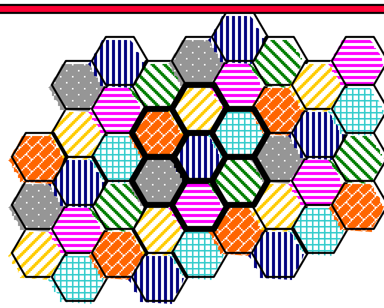


- each user has different code
  ~ speaks different language
- Direct Sequence Spread Spectrum
  – code used to encode data
- Frequency Hopping Spread Spectrum
  – code used to select frequency sequence

Carrier sense multiple access (CSMA)

- sense medium before transmit
  – if free, transmit information
  – if collision, back-off and re-send information
- system implications similar to TDMA
- BUT,
  + no synchronization necessary
  – no guaranteed bandwidth
    ➡ used for data communications
    e.g. wireless LAN

Cellular Communications System



- large number of users
- cellular system
  - stations far enough
    ➡ frequency reuse
  - far ~ transmitted power
- Co-channel interference
  - ~ distance 2 co-channel cells/cell radius
  - power independent
  - 7 reuse: ratio = 4.6 (18dB)
- Base-station & mobile unit
  - forward/up link: base ➡ mobile
  - reverse/down link: mobile ➡ base
  - hand-off: switch base stations

Channel characteristics

- Path-loss:
  - propagation characteristics
- Multi-path fading:
  - direct & reflected signals interfere at rcv
- Delay Spread:
  - direct & delayed signals interfere

➡ fast & large variations in signal strength in moving receiver

➡ "frequency blocking" in stationary receiver

Standards - Some Examples

- Advanced Mobile Phone Service (AMPS)
- North American Digital Standard (NADS) IS-54
- IS-95 DS CDMA - Qualcomm CDMA
- Global System for Mobile Communications (GSM)
- Digital Enhanced Cordless Telephone (DECT)
- IEEE 802.11
- HiperLAN
- ....

GSM

- **G**lobal **S**ystem for **M**obile Communications
- FDD:
  - RCV: 935-960 MHz
  - XMT: 890-915 MHz
- FDMA & TDMA:
  - 200 kHz Channels
  - frame = 8 slots: 4 rcv & 4 xmt
  - RCV & XMT slot offset by 3 time slots
  - data rate ~ 270kbits/sec
- GMSK modulation
  - constant envelope - BT=0.3

GSM Type approval (summary)

- Receiver
  - BER ~10^{-3} or S/N @ demodulator > 9dB
  - signal range: -102dBm to -15dBm

  <u>for signal of -99dBm</u>:

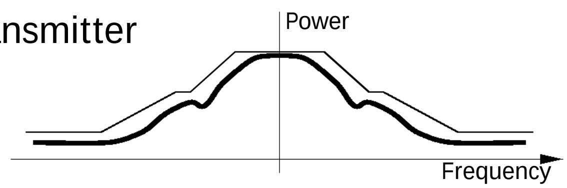
  - blocking: in band: -43 up to -23dBm
    out of band: 0dBm
  - inter-modulation: -49dBm @800kHz & @1600kHz

  <u>for signal of -82dBm</u>:

  - co-channel test: 9dB smaller interferer in same channel
  - adjacent channel (@200kHz): 9dB larger
  - alternate channel (@400kHz): 41dB larger

GSM Type approval (summary)

- Transmitter

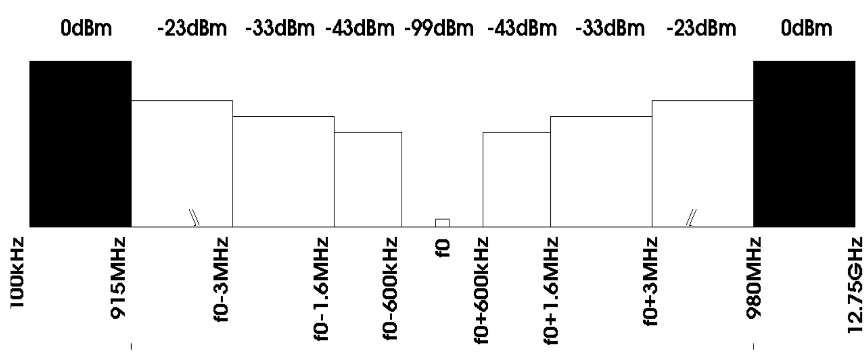


  - close-in: modulation spectrum (spectral mask)
  - wide-band: noise spectrum e.g.
    - noise@3MHz < -115dBc/Hz
    - noise@6MHz < -130dBc/Hz
    - noise@25MHz < -130/-136dBc/Hz
  - average phase error < 5 deg.RMS
  - output power
    - up to 2-3 Watt: 33-35dBm
    - power control: 28dB
  - carrier leakage < 40dBc

Receivers

Radio Receiver Problem (e.g. GSM)

- small signal: down to -102dBm
- narrow band signal: 200kHz on ~900MHz
- very hostile environment ➡ interference
  - e.g. blocking signals ~**100dB** larger than signal !!



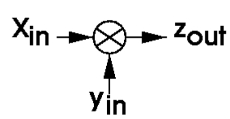
Filter as RCV

- e.g. GSM fo=900MHz
  BW=200kHz
- Quality factor: ~4500
  - high Q ➡ high loss ➡ high NF
- High rejection & sharp filter
- Tunable filter
  - center frequency accuracy

No Filter Technology available

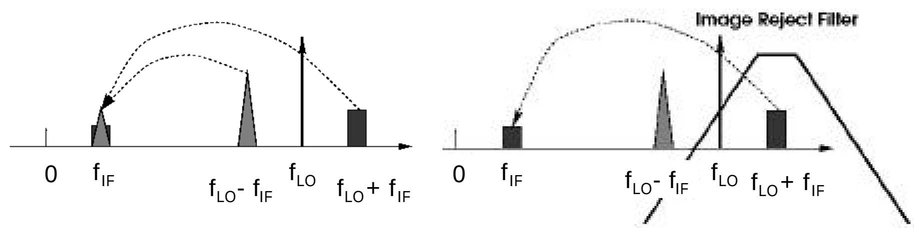
Heterodyne Receiver

- down-convert signal to lower fixed intermediate frequency (IF) for filtering
  ➡ Q lower
  ➡ fixed frequency
- Mixer



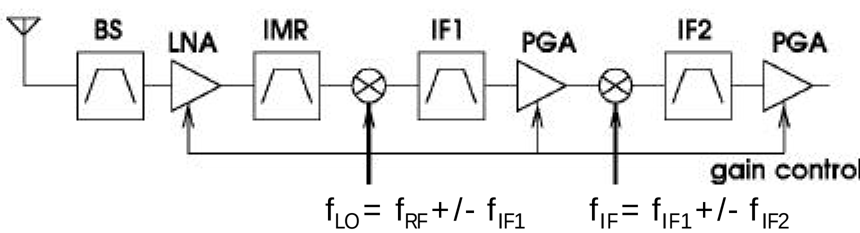
  - $z_{out} = K \cdot x_{in} \cdot y_{in}$
  - frequency translation:
    - x_{in}@ω_1 & y_{in}@ω_2 ➡ z_{out}@$|\omega_2 +/- \omega_1|$
  - conversion gain:
    - $CVG = z_{out} / x_{in} = K \cdot y_{in}$

Heterodyne Receiver: IMAGES ....



- f_o+f_{IF} & f_o-f_{IF} mix with fo to same f_{IF}
- potential interference
- add IMAGE REJECT FILTER before mixer

Heterodyne: choice of IF



- high IF + more relaxed image filter
  + smaller IF filter
  - higher Q ➡ higher loss
- multiple IFs: distribute channel filtering
- filter-amplify-filter-amplify
- gain at different frequencies: no oscillation risk

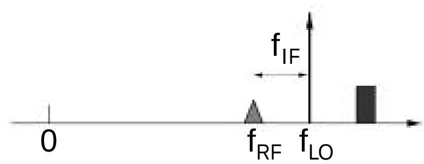
Mixer Spurious Responses

- image frequency
- feed-through to IF: (LO ➡ IF and RF ➡ IF)
- mixer: never only second but also higher order
  - e.g. spurious response table for double balanced mixer

			f_{LO}	$2f_{LO}$	$3f_{LO}$	$4f_{LO}$	$5f_{LO}$	$6f_{LO}$
6	f_{RF}	-100	-92	-97	-95	-100	-100	-95
5	f_{RF}	-90	-84	-86	-72	-92	-70	-95
4	f_{RF}	-90	-84	-97	-86	-97	-90	-100
3	f_{RF}	-75	-63	-66	-72	-72	-58	-86
2	f_{RF}	-70	-72	-72	-70	-82	-62	-75
1	f_{RF}	-60	0	-35	-15	-37	-37	-45
			-60	-60	-70	-72	-72	-62

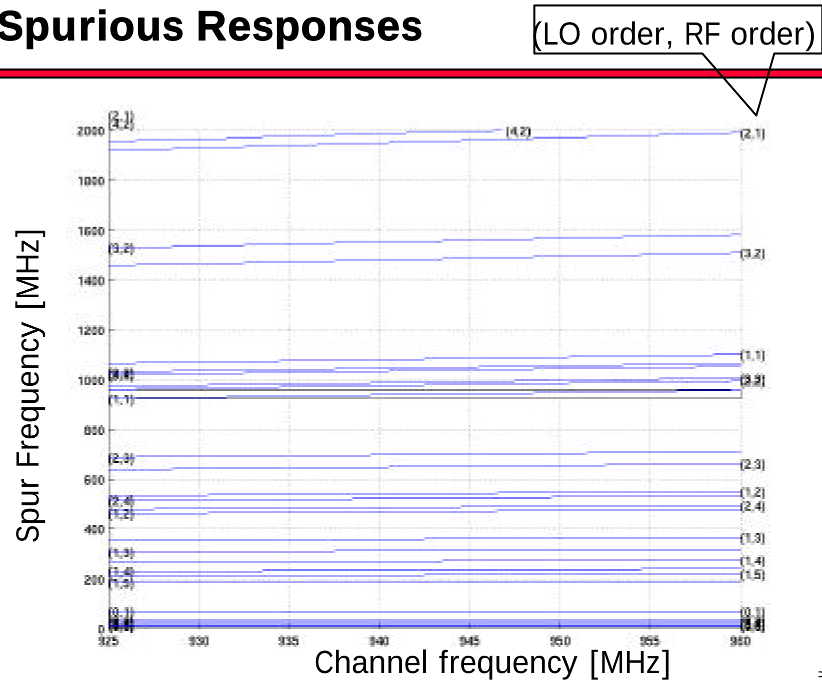
- frequency planning

Frequency Planning: spurious responses

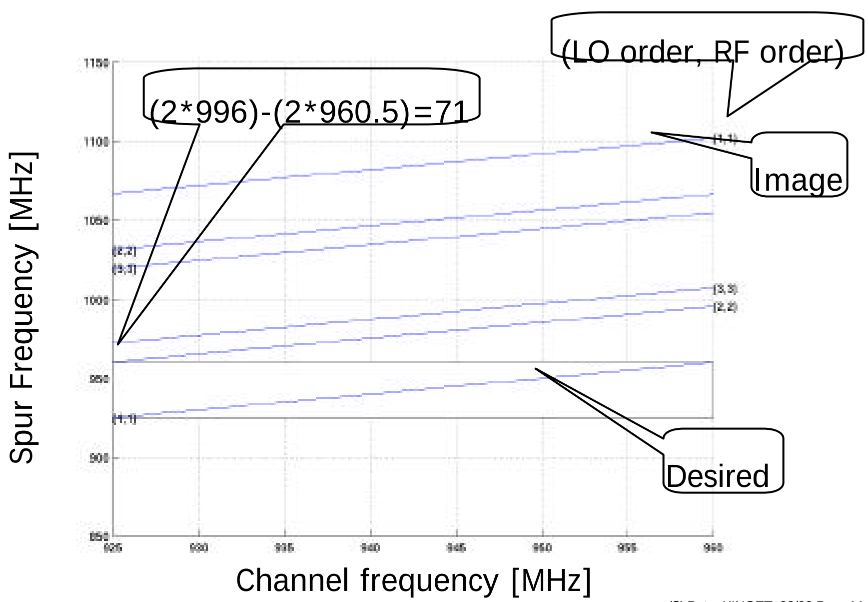


- e.g. low side injection difference mixer
  - $f_{IF}=f_{LO}-f_{RF}$
  - e.g. GSM RCV
    - RF in: 925-960MHz
    - IF: 71MHz
    - LO: 996-1031MHz
- find all spur frequencies f_s
  - $|n\ f_s +/- m\ f_{LO}\ | = f_{IF}$
  - n: 0, 1, 2 ....; m: 0, 1, 2, ...

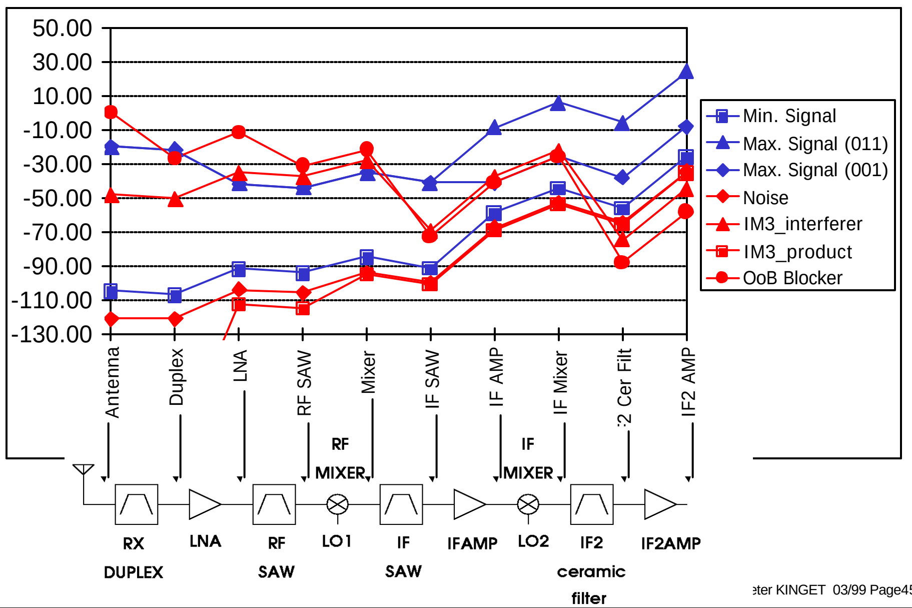
Spurious Responses



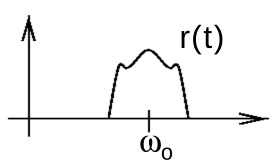
Spurious Responses (zoom)



Level Diagram



Band-limited signal: Complex envelope

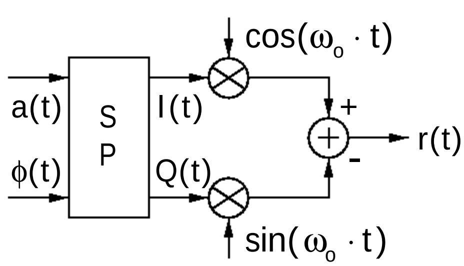


$$r(t) = a(t)\cdot\cos(\omega_o\cdot t + \phi(t))$$

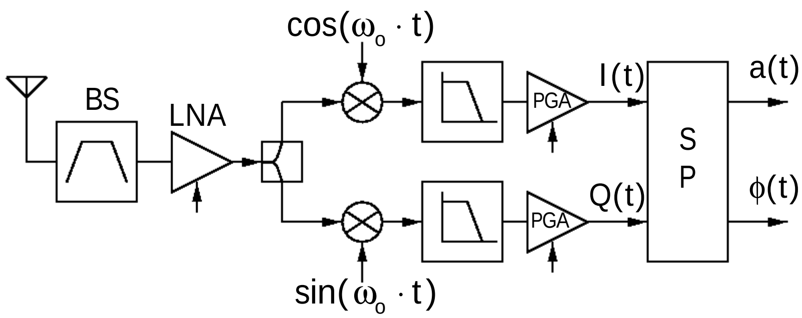
$$r(t) = I(t)\cdot\cos(\omega_o\cdot t) - Q(t)\cdot\sin(\omega_o\cdot t)$$

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

$$\phi(t) = \tan^{-1}\left(\frac{Q(t)}{I(t)}\right)$$



Homodyne Receiver

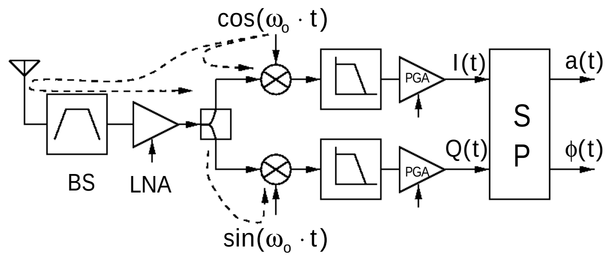


- $f_{LO}=f_{RF}$ ➡ $f_{IF}=0$
- image=signal
- quadrature down-converter
- lowpass filter does channel selection

Homodyne design issues (1)

- Lowpass filters for channel selection
  - can be integrated on IC
  - high dynamic range required
    - preceded by limited gain or filtering
  - a lot of (programmable) gain at DC
    - parasitic feedback can cause stability problems
  - DC offset
  - 1/f noise

Homodyne design issues (2)



- Time-varying DC offsets
  - self-mixing
    - LO leakage
    - RF leakage
- LO emission
- I/Q mismatches

Homodyne design issues (3)

- Even order distortion
  - IM2@LNA -> LF signal -> mixer RF/IF feed-through
  - IM2@Mixer -> LF signal & DC
  - differential circuits
  - but P/A single-ended -> antenna SE -> LNA SE
  - single-ended to differential conversion at RF ....

Why not for IF

- Passive IF filters: high DR
- DC offset out of band: ac coupling
- IM2 out of band: ac coupling
- @IF 1/f noise low
  DC offset out of band
- $f_{LO}=f_{RF}$ +/- f_{IF} : emission filtered
- Modern IF: zero-IF back-end to go into DSP

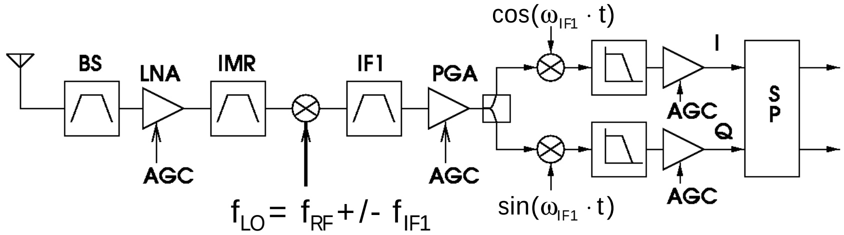
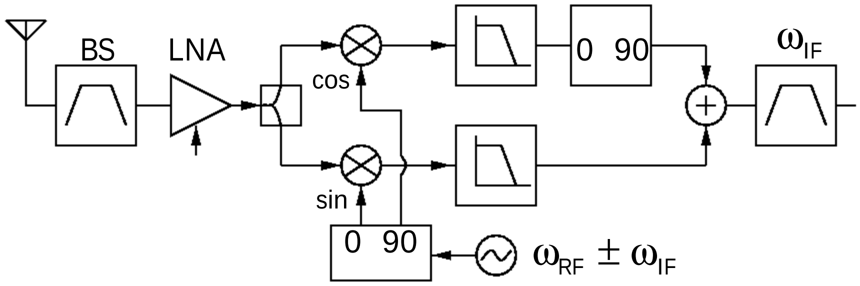
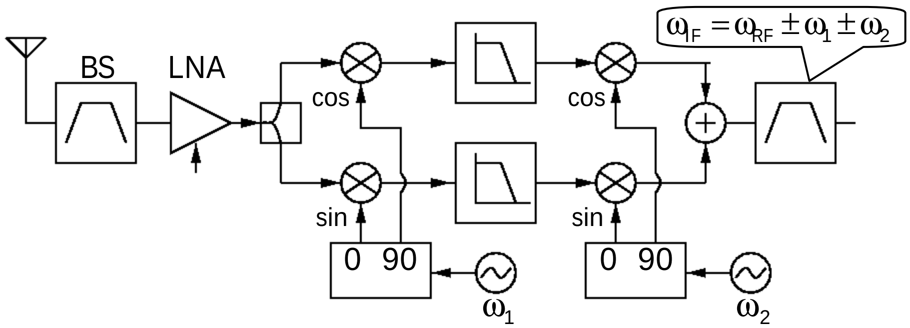


Image Reject Receiver: Hartley



- no IMR filter
- image rejection depends on
  - quadrature accuracy
  - gain matching
- 90 degrees shift in signal path

Image Reject Receiver: Weaver



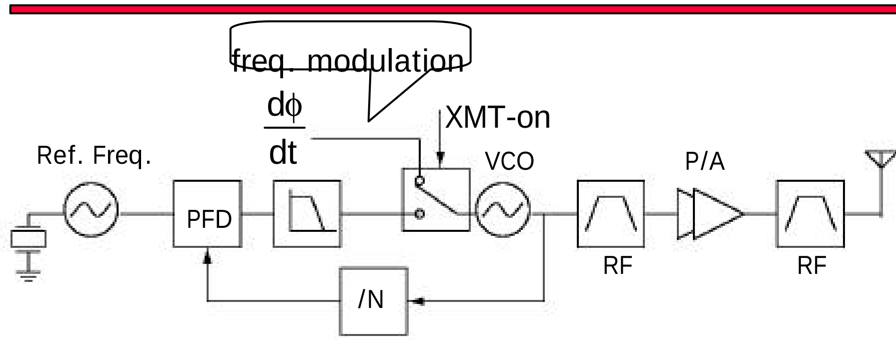
- use 2nd quadrature mixing stage instead of 90deg. shift
- additional secondary image

Transmitters

Transmitters - Overview

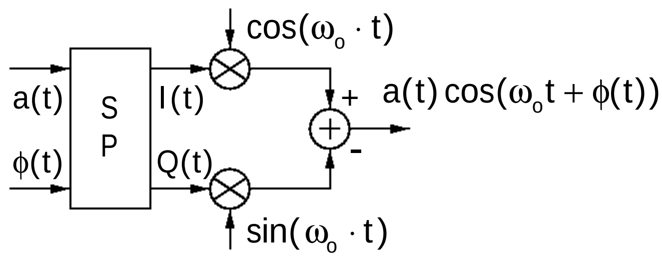
- Basic functions:
  - modulation:
    - encode the information on a waveform's amplitude, phase or frequency
  - up-conversion:
    - move signal to desired RF carrier frequency
  - power amplification
    - amplify signal to deliver wanted power to antenna for emission

Direct VCO modulation



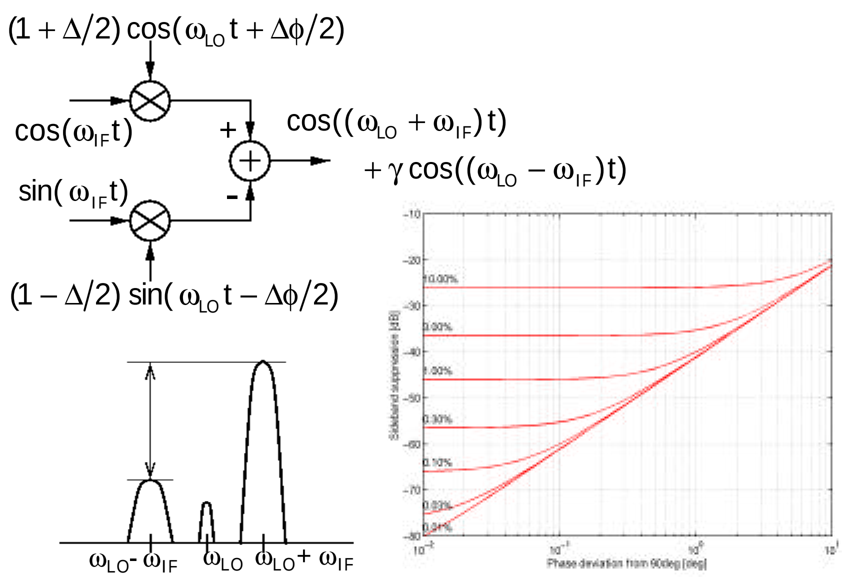
- only constant envelope modulation
- VCO in open loop during XMT
  - frequency drift
  - pushing/pulling
  - close-in VCO noise
  - switch time XMT/RCV includes lock time
- compact

Quadrature Modulator

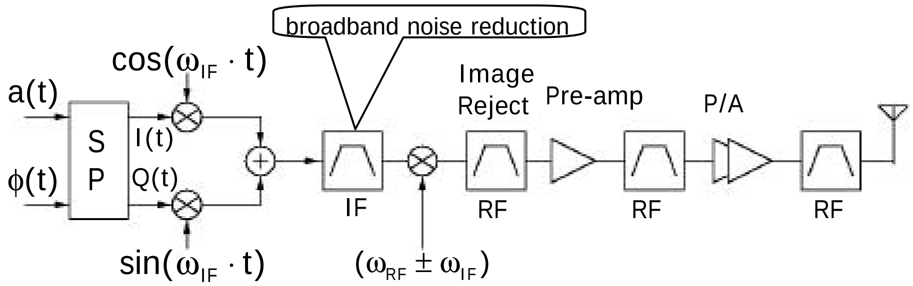


- Any modulation format
  - see complex envelope
- But unwanted sideband when
  - non perfect quadrature
  - gain mismatches

Quadrature modulator: Side-band rejection

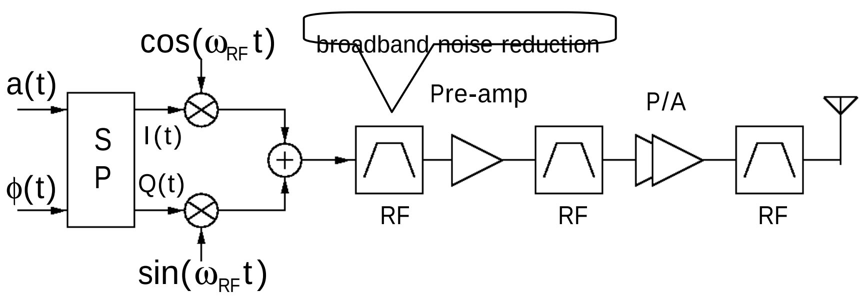


Multi-step Up-conversion



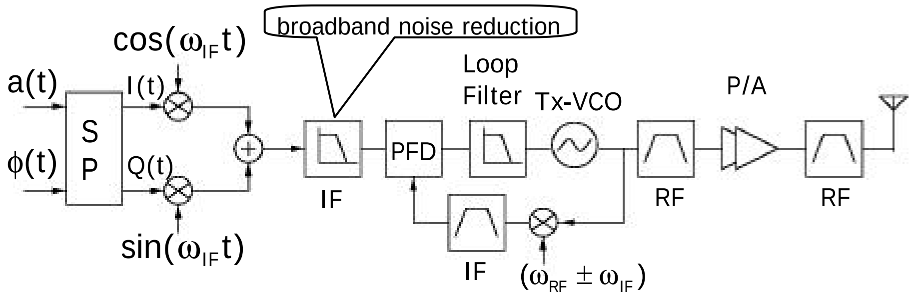
- good image reject filter necessary
- potential for other spurs
- extra filter to reject broadband noise

Direct Up-conversion



- no IF and no spurs: relaxed filtering
- extra filter to reject broadband noise
- potential RF VCO re-modulation by P/A out
  - VCO shielding
- quadrature RF signal required

Indirect VCO modulation



- only constant envelope modulation
- loop filter BW > signal BW
- low broadband noise !
- Tx-VCO: high power & low noise (e.g. P_{out} 10dBm typ. in GSM)
- potential for spurs

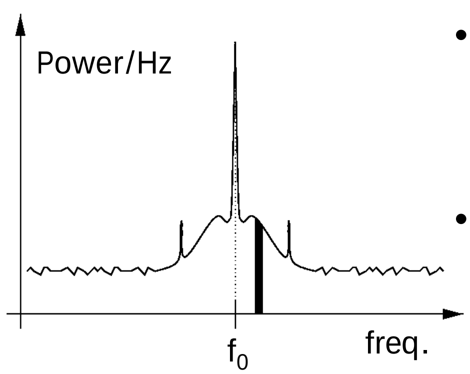
Power amplifier & output filters

- TDD: P/A - switch - antenna
  - ~1dB loss in switch
- FDD: P/A - duplexer - antenna
  - ~2-3dB loss in switch
  - 30-50% of P/A power dissipated in duplexer
- average efficiency P/A << 50%
  - depends strongly on modulation format
- P_{out}/P_{DC} << 25%

Transceiver design

Frequency Synthesizer

- 3^{rd} subsystem in transceiver



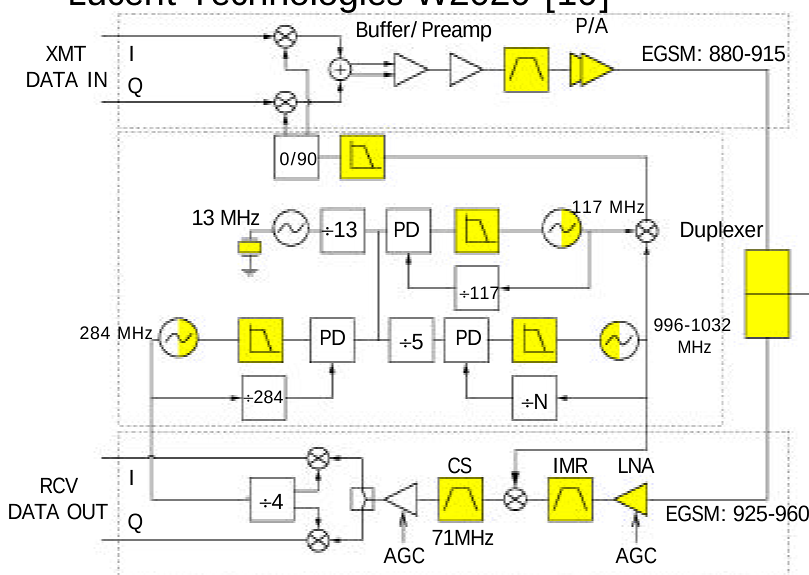
- RCV:
  - phase noise level in side bands
  - discrete spurs
- XMT:
  - RMS phase error = integrated phase noise
  - wideband noise
  - discrete spurs

Transceiver Design

- ***Meet the standard !!!!***
- Architecture selection and system design
  - Bill of materials
  - Frequency planning:
    - # VCOs & spurious responses
  - Power consumption:
    - Transmitter (P/A) talk time
    - Receiver standby time
  - Partioning
    - Hardware/Software
    - Analog/Digital
- Time to market & Price & Package

GSM Transceiver Example

- Lucent Technologies W2020 [10]



Recent Transceiver Architectures

- Some Trends:
  - integration & cost reduction
  - dual band
  - multi standard
- Some Techniques
  - Zero-IF
  - Low-IF
  - Double Low-IF
  - Wide-band-IF
  - IF sampling
  - Δ–Σ decimation filter as channel select
  - Software Radio
  - ....

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