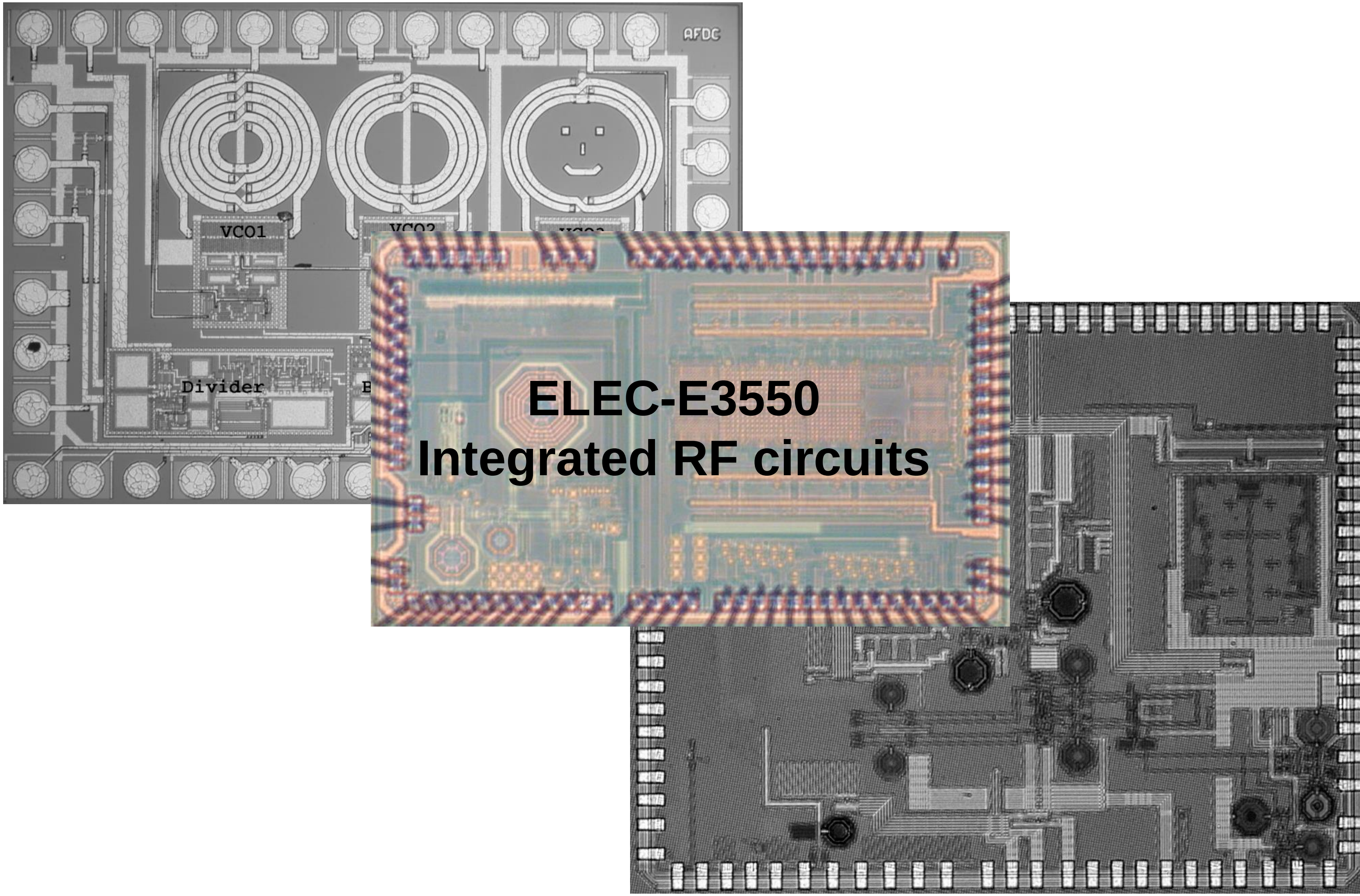
ELEC-E3550
Integrated RF circuits

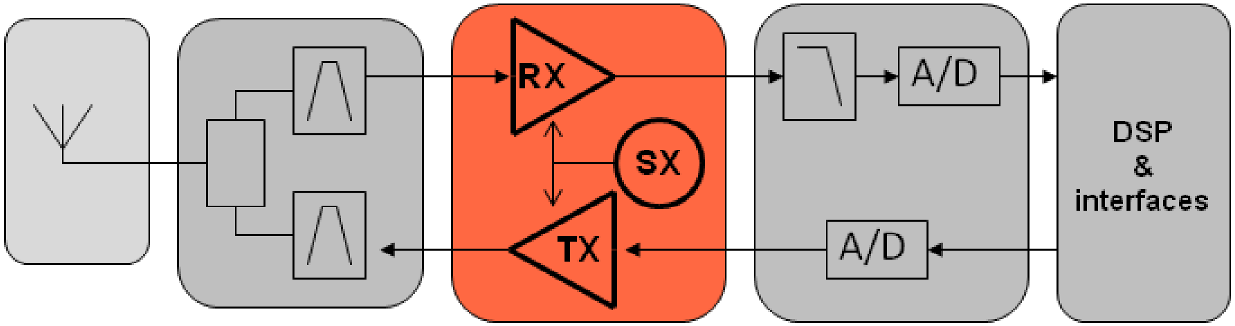


Aalto University
School of Electrical Engineering

Department of Electronics and Nanoengineering
Kari Stadius, Saeed Naghavi, Jian Gao

Integrated RF circuits
Spring 2022

Transceiver Architectures and Concepts



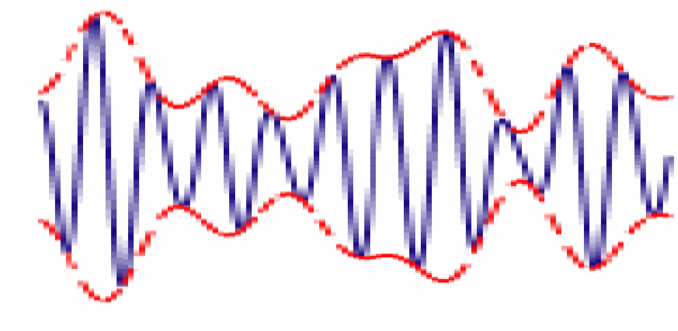
1. Brief reminder on modulation and demodulation
2. Transmitter architectures
3. Receiver architectures
4. Gain, noise and nonlinearities

Modulation and Demodulation

- Information is combined to or separated from the carrier wave
- Modulation schemes
  - Enables to transfer LF information at HF carrier
  - Robust against noise and interference
  - Spectrum efficient
- Analog systems: time-vary a single parameter of a general carrier wave

Core idea of radio comm

$$s(t) = A \cos(\omega t + \phi)$$

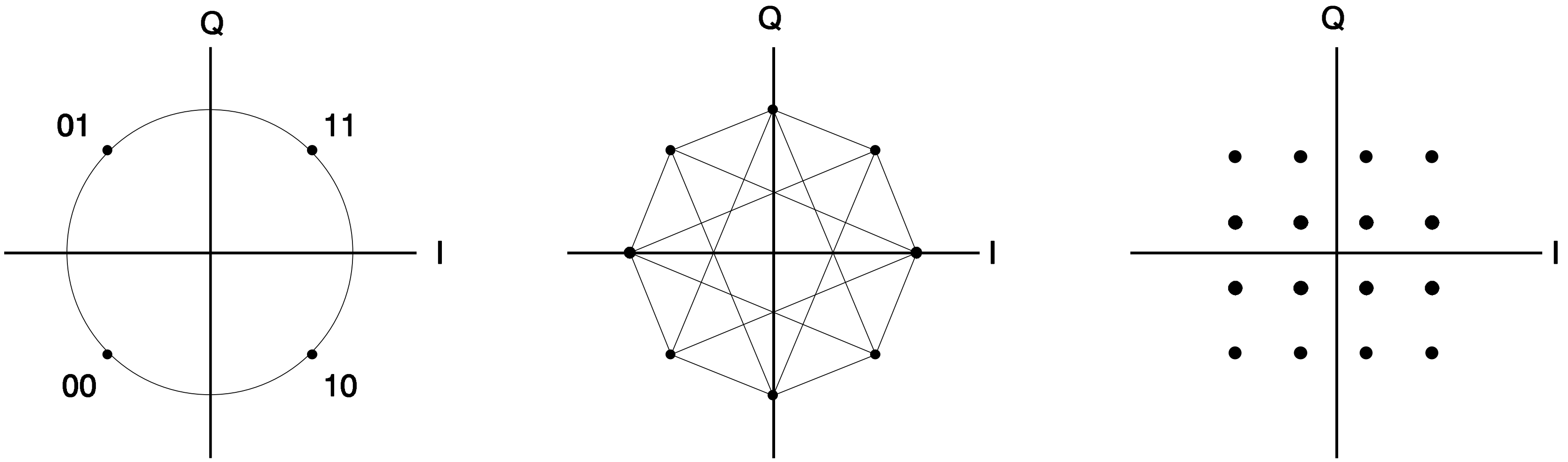


- AM
- FM
- PM

OOK ≈ Morse coding; Simplest ”modulation”

Modulation and Demodulation

- Modern communications systems utilize digital modulation schemes (modulating baseband signal is digital)



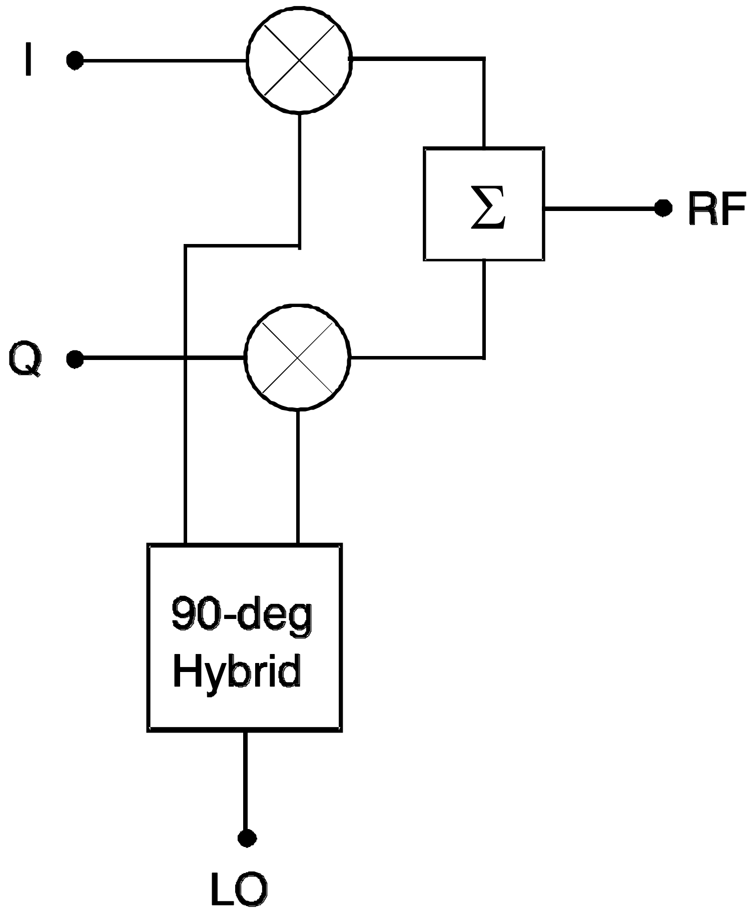
(a) (b) (c)

QPSK
(Quadrature Phase-Shift Keying)

π/4-QPSK

QAM-16
(Quadrature Amplitude Modulation)

IQ-Modulator



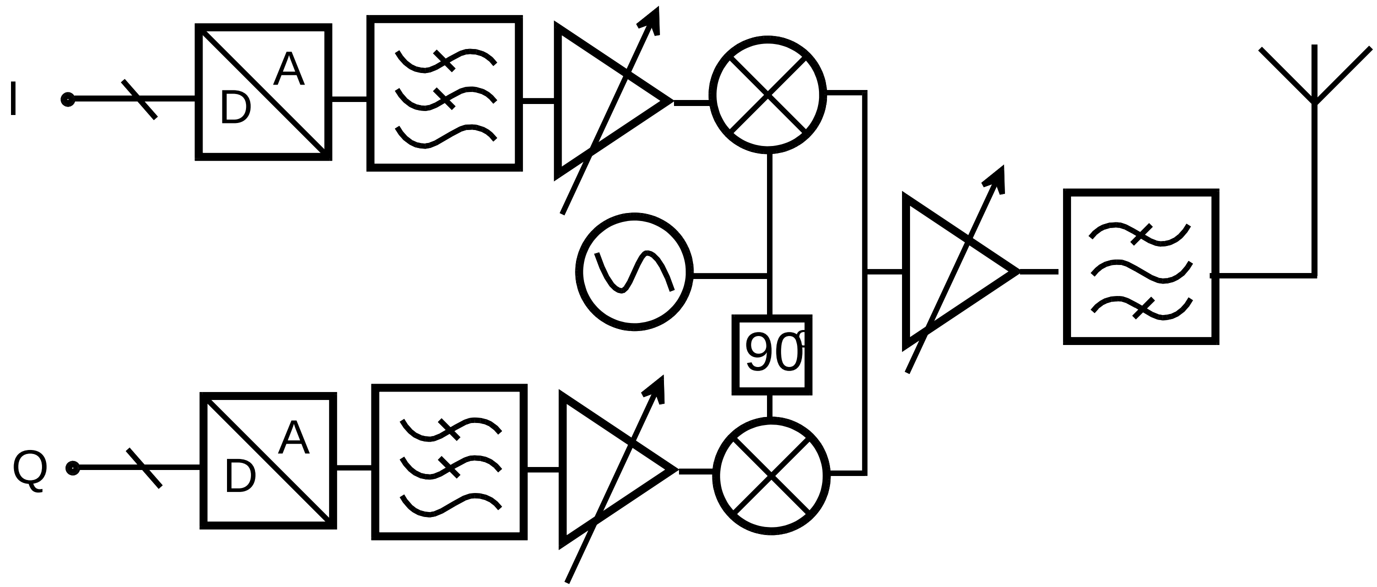
$$v_{out} = k(t)\cos(\omega t - \phi(t)), \quad \text{where}$$

$$k(t) = a\sqrt{i^2(t) + q^2(t)} \quad \text{and}$$

$$\phi(t) = \arctan\left(\frac{q(t)}{i(t)}\right).$$

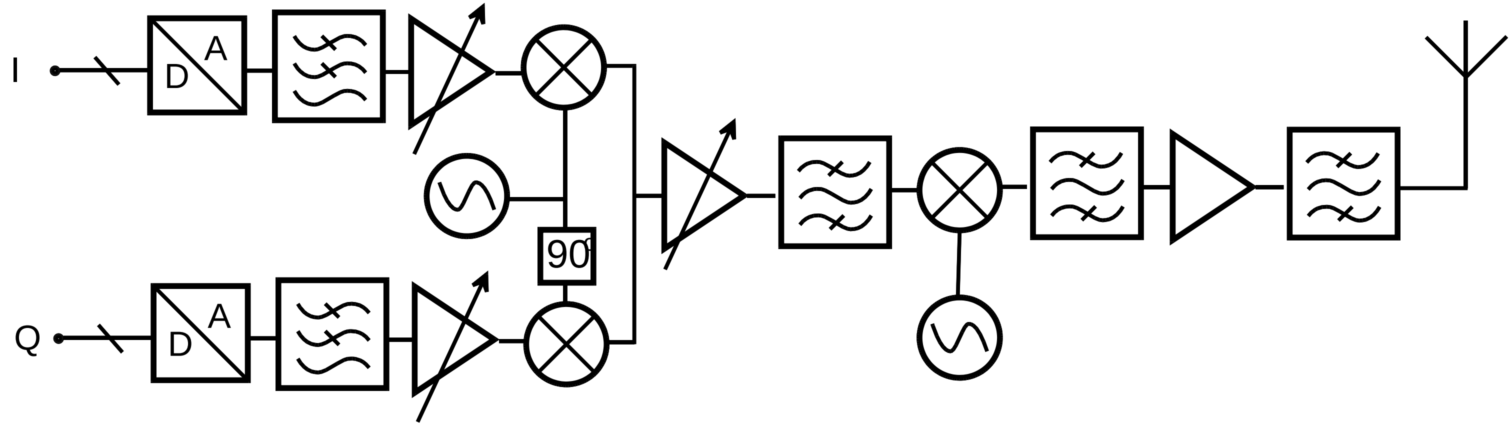
Department of Electronics and Nanoengineering
Kari Stadius, Saeed Naghavi, Jian Gao

Direct-Conversion Transmitter



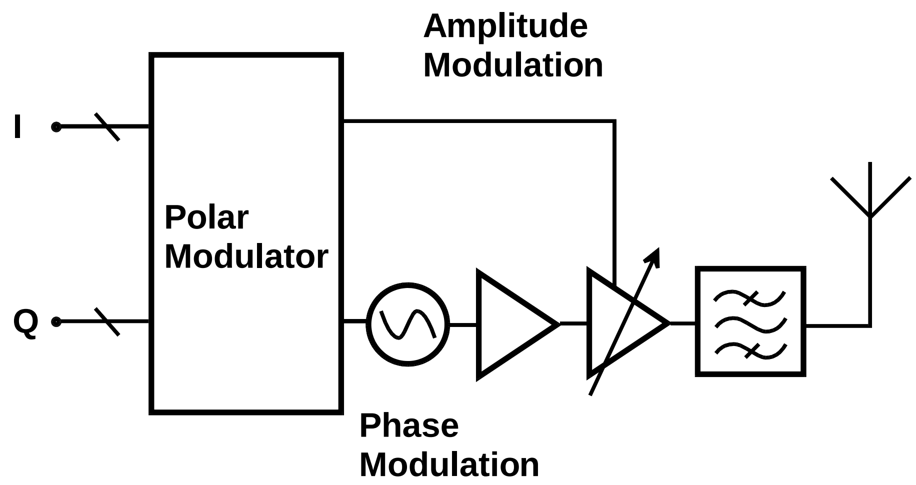
- High integration level
- LO at the same frequency as TX signal

Up-Converting Transmitter



- Two or more up-conversions
- IQ-modulation at lower frequencies → Improved performance
- BPFs difficult to integrate
  - High sideband suppression with BPF after second up-conversion

Polar Transmitter



- Phase and amplitude information separated in polar modulator (digital separation)
- Use of nonlinear PAs in transmitter $\rightarrow$ Increased efficiency
- Bandwidth requirement of AM path increased compared to IQ-signal

Out-Phasing aka LINC

LINC = linear amplification with nonlinear components

NO Amplitude info = Non-linear PA ok!

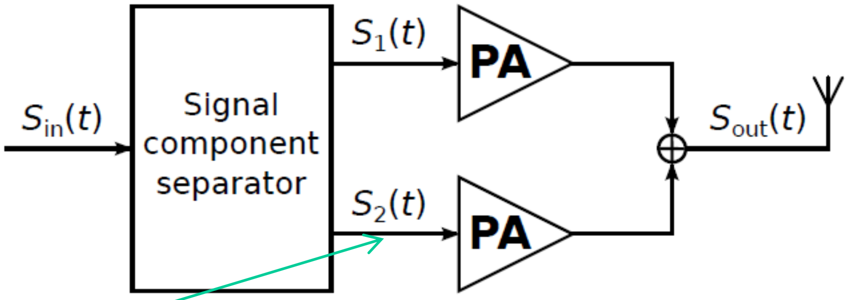


Figure 2.3: Block diagram of the outphasing transmitter.

similarly to the output of the polar transmitter. The two constant-envelope components are

$$S_1(t) = V_0 \cos(\omega t + \phi(t) + \theta(t)) \qquad (2.7)$$

$$S_2(t) = V_0 \cos(\omega t + \phi(t) - \theta(t)), \qquad (2.8)$$

where $\theta(t)$ is the outphasing angle. These signals are amplified with gain G and combined, resulting in the output signal

$$S_{out}(t) = GS_1(t) + GS_2(t). \qquad (2.9)$$

This sum is equal to

$$S_{out}(t) = 2GV_0 \cos(\omega t + \phi(t)) \cos(\theta(t)). \qquad (2.10)$$

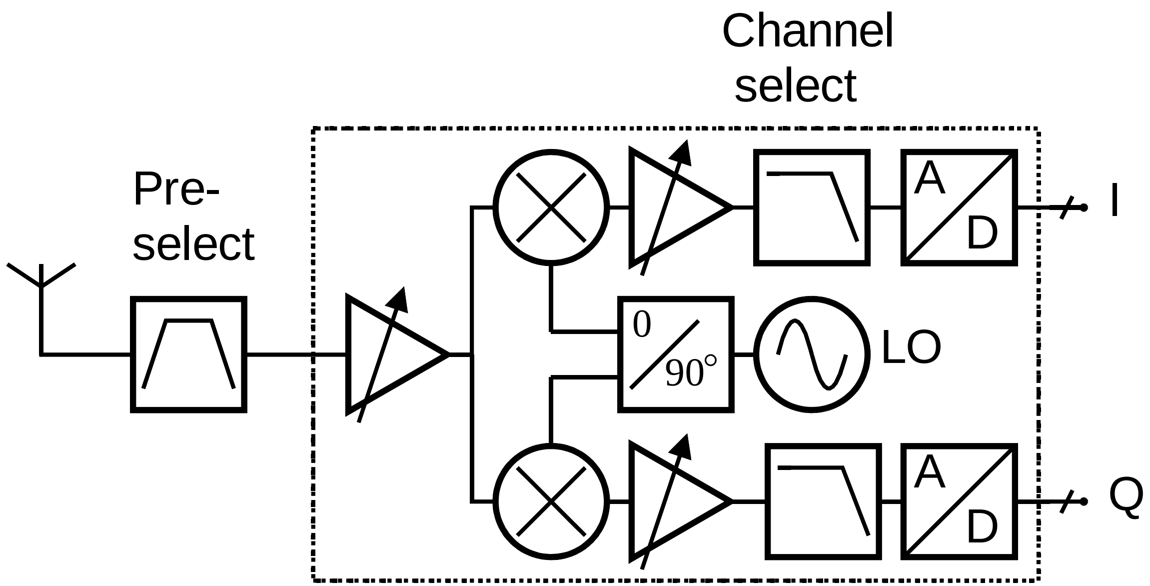
By choosing the outphasing angle to be

$$\theta(t) = \arccos \frac{E(t)}{V_0}, \qquad (2.11)$$

the output signal becomes the input signal amplified with gain $2G$:

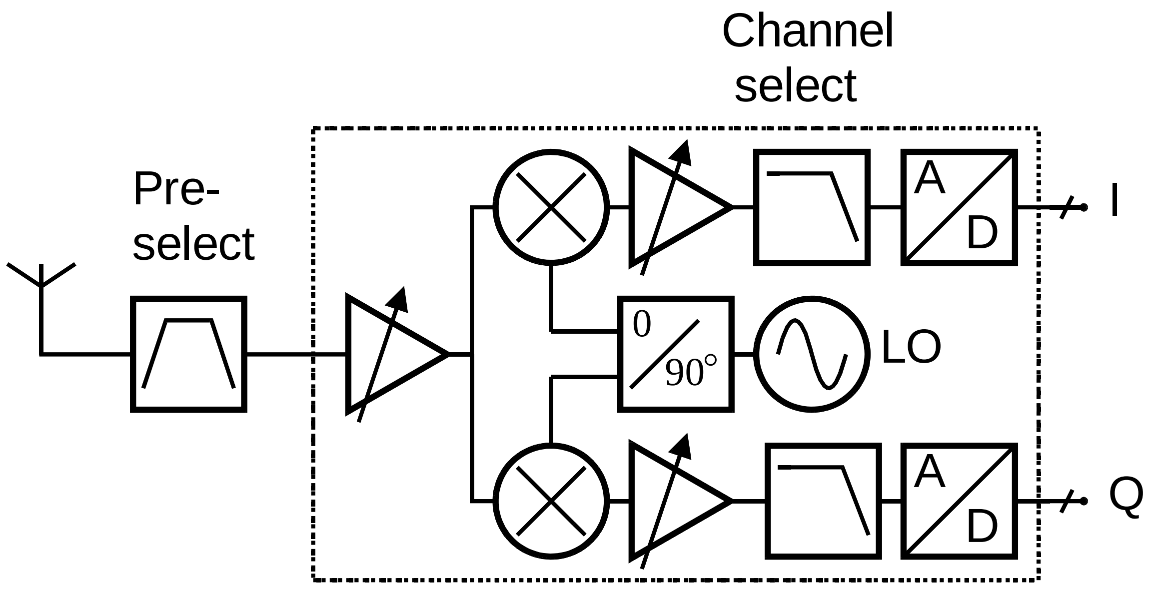
$$S_{out}(t) = 2GE(t) \cos(\omega t + \phi(t)). \qquad (2.12)$$

Direct-Conversion Receiver



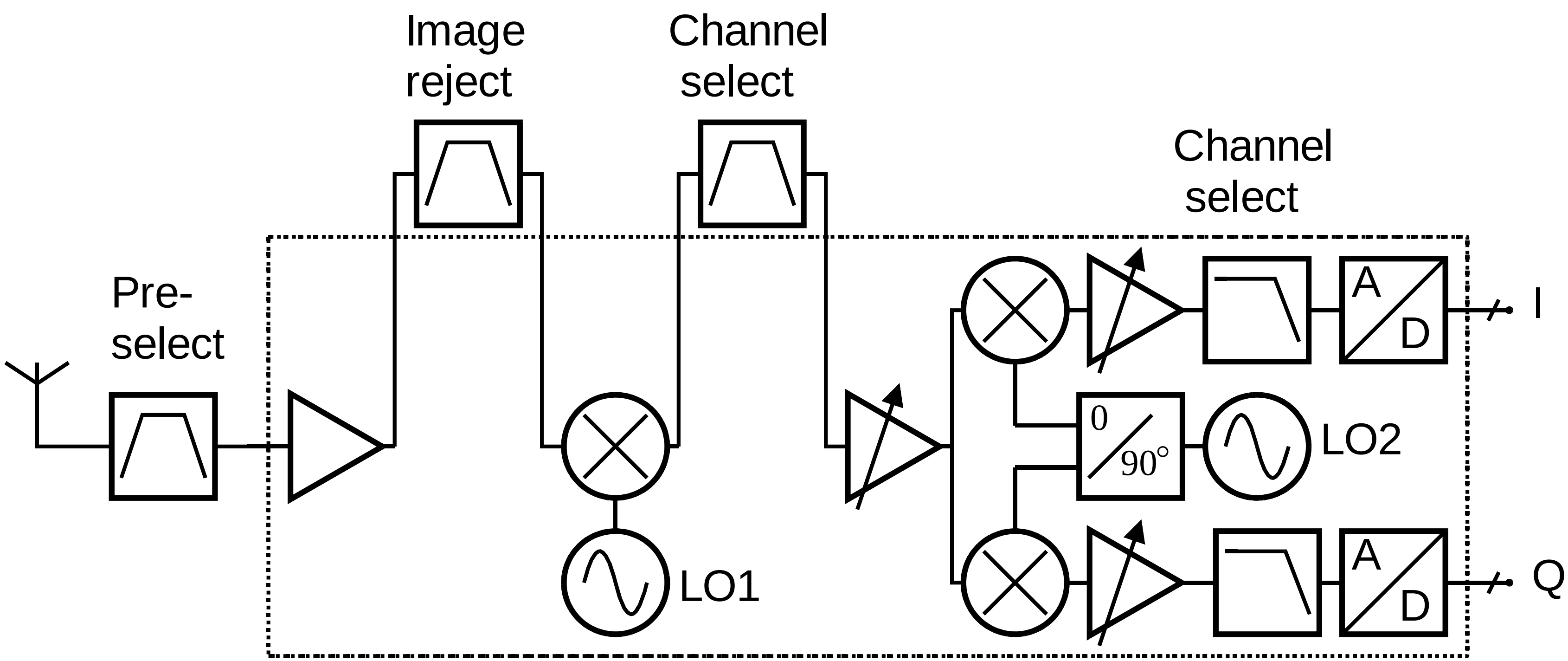
- Signal demodulation is carried out at the signal frequency.
- Complexity of RF circuitry is minimized and receiver integration level maximized → Work-horse of modern RF ICs
- In the RF section two problems arise: LO radiation and DC-offsets.

Low-IF Receiver



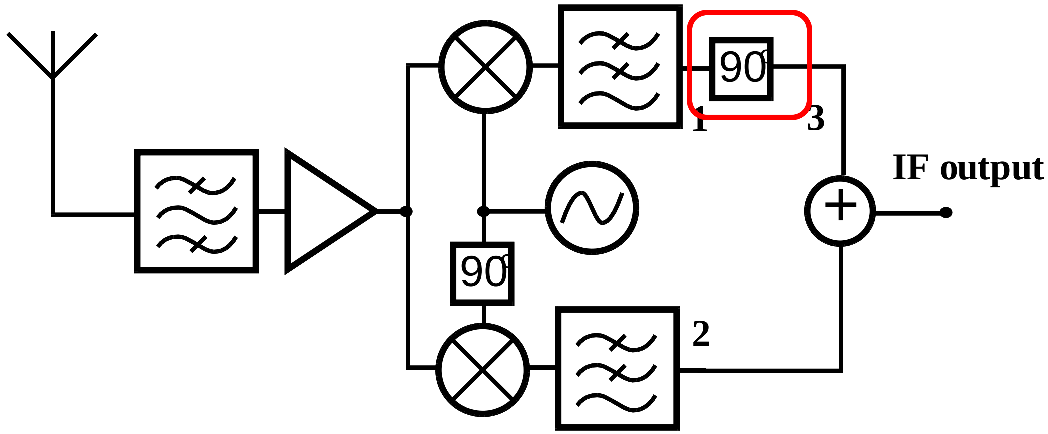
- Similar as direct conversion receiver
- Down-converted signal at low IF, e.g. 1 MHz
- No DC-offset problem
- Image must be suppressed sufficiently
- Wideband reception problematic

Superheterodyne Receiver



- Ability to achieve large dynamic range with moderate active elements,
- Good sensitivity and selectivity, “the best architecture”
- Requires high-quality filters → Integration difficult (impossible with CMOS)

Image-reject Hartley Receiver

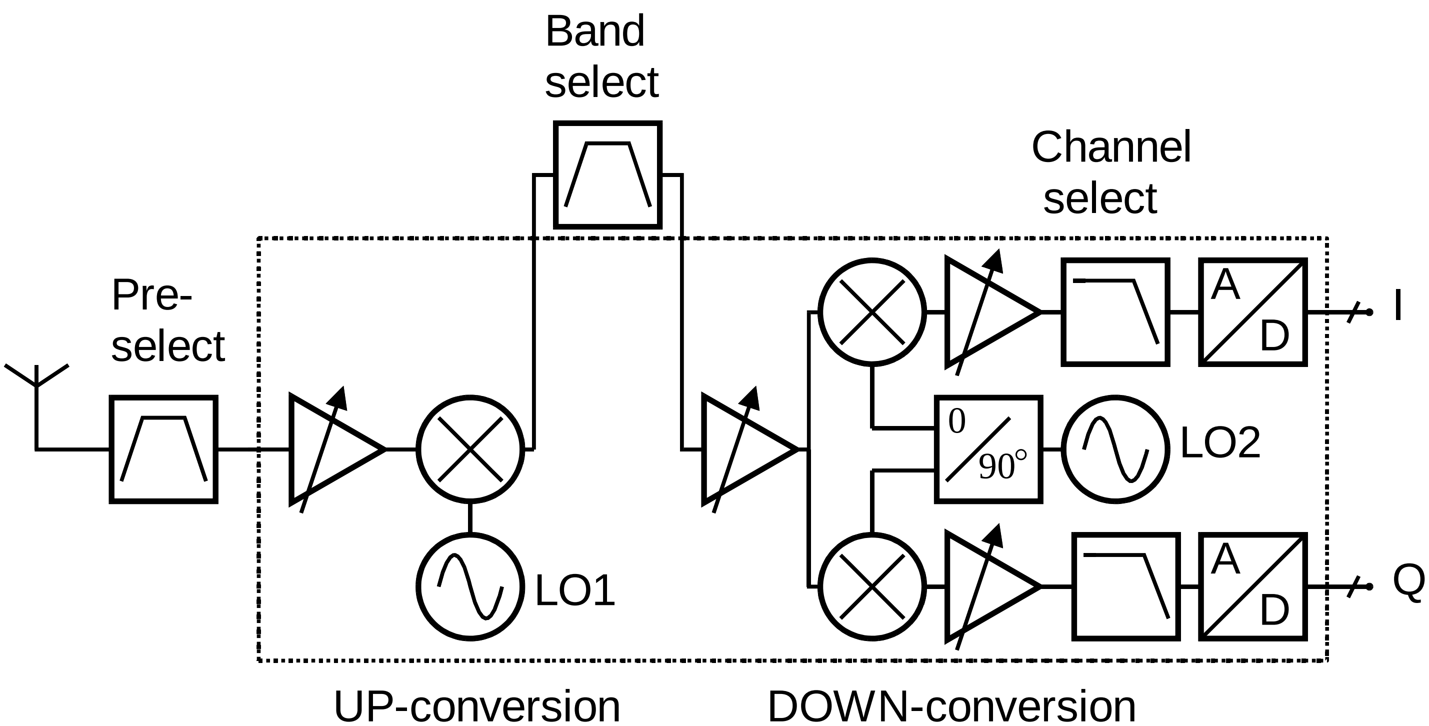


- No I/Q outputs
- Image frequency attenuated with 90 deg phase shift at IF

- Weaver architecture is an alternative to this one

Department of Electronics and Nanoengineering
Kari Stadius, Saeed Naghavi, Jian Gao

Double-Conversion Receiver



- Very wideband RF signal -- LO is a challenge
- This architecture relieves SX requirements

Why so many receiver architectures ?

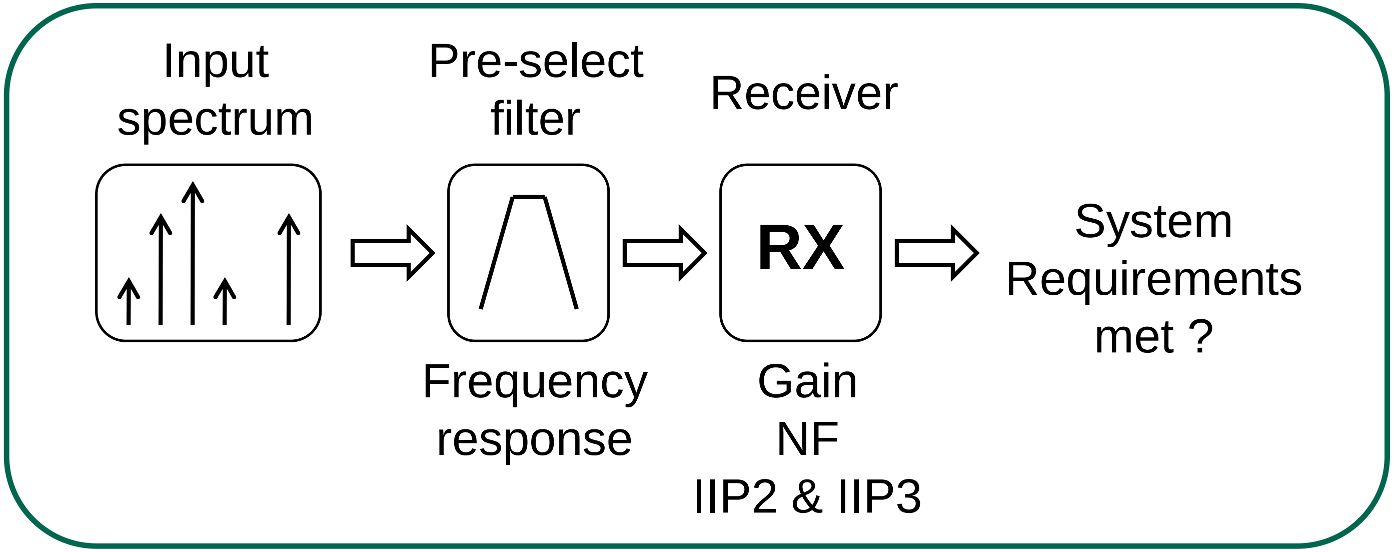
- Wireless radio environment is very hostile; interfering signals!
- TX does not suffer from this challenge
- System standards dictate the needed features of the receiver
  - sensitivity, dynamic range, power, prize, size
- Manufacturing technology sets its own boundaries

- DCR is the present-day winner for moderate performance, low price radios, but keep other options in mind as well !!

- For instance, new performance requirements or a technology that enables new circuit techniques may alter the situation

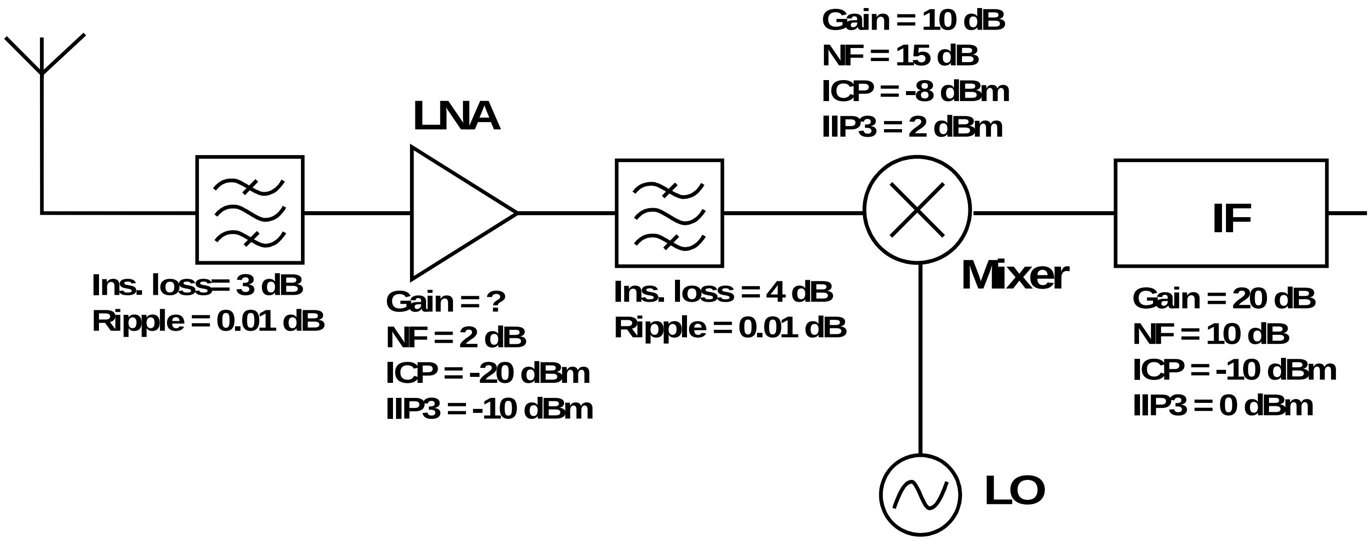
Receiver Chain Design

RF IC designers need to carry out block design of transceivers, not only circuits!



- Gain
- Noise Figure
- Nonlinear effects
    - Gain compression
    - Blockers
    - Intermodulation

Receiver Chain Design



Gain

Power gain is simply

$$G_p = \frac{P_{OUT}}{P_{IN}}$$

In classic RF engineering several definitions are used (operating power gain, transducer power gain, available power gain, unilateral transducer power gain), but they are rarely used in RF IC jargon.

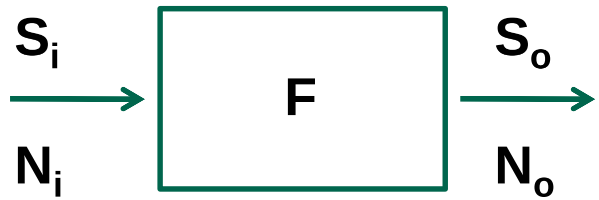
Power gain is often problematic in RF IC design since impedance level of a node is not specifically defined and there is no impedance matching.

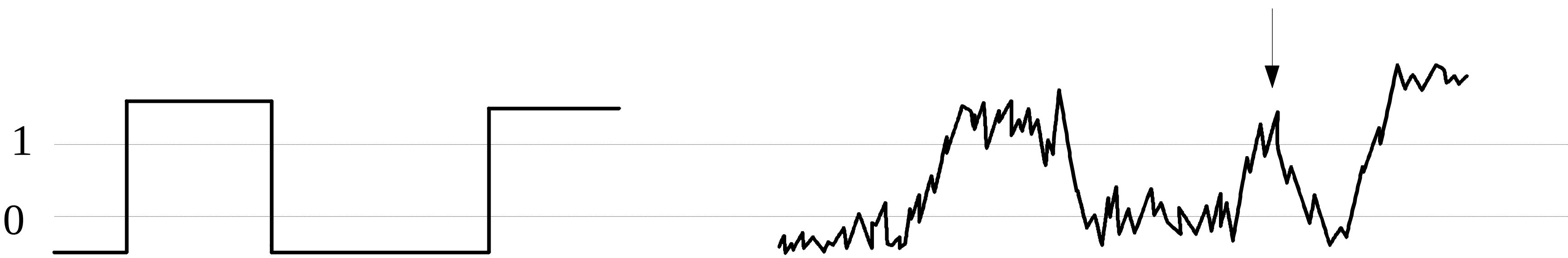
Voltage gain is

$$A_v = \frac{V_{out}}{V_{in}}$$

Some circuits (filters, some mixers) attenuate signals: Att = - Gain

Noise in Circuits





$$\boxed{F = \text{Noise factor} = \frac{S_i / N_i}{S_o / N_o}}$$

Noise Figure NF = 10 log (Noise factor)

Noise in Circuits (cont.)

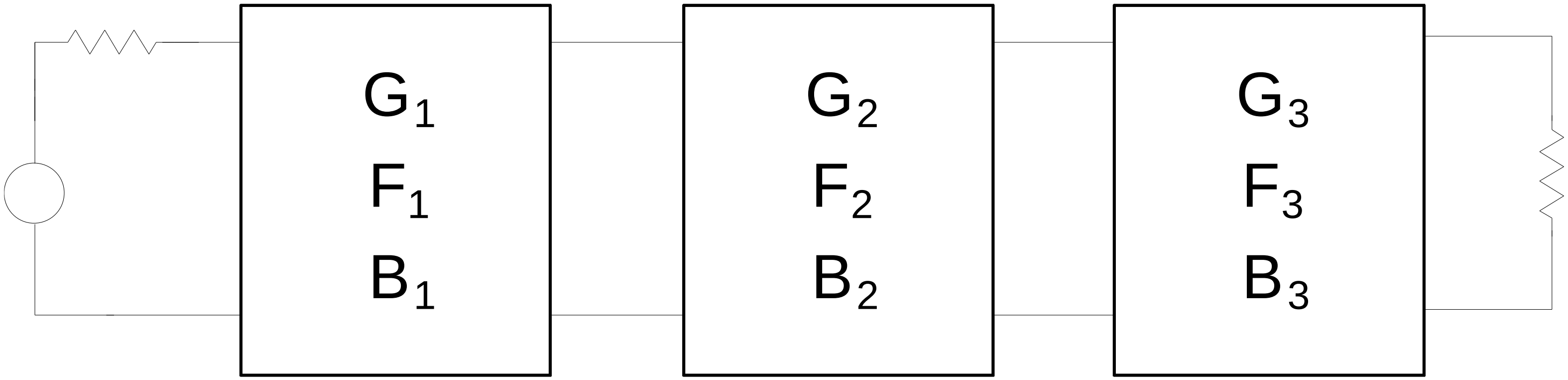
$$\boxed{F = \frac{S_i / N_i}{G S_i / N_o} = \frac{N_o}{G N_i}}$$

$$\boxed{F = \frac{N_o}{G N_i} = \frac{G(N_i + N_a)}{G N_i} = 1 + \frac{N_a}{N_i}}$$

$$\underbrace{\frac{N_a}{N_i}}_{\text{no signal here!}}$$

- N_a = added noise generated by the circuit and referred to the input of the circuit
- N_i is defined to be the thermal noise of the generator resistor at the standard temperature T_o=290K: $N_i = kT_oB$

System Noise Figure



$$N_{A1} = (F_1 - 1)kTB_{1,3} \quad \leftarrow \text{bandwidth through path } 1\ldots3 \;= B_{tot}$$

$$N_{A2} = (F_2 - 1)kTB_{2,3} \quad \leftarrow \text{bandwidth through path } 2\ldots3$$

$$N_{A3} = (F_3 - 1)kTB_{3,3} \quad \leftarrow \text{bandwidth through } 3$$

$$N_{A,tot} = N_{A1} + \frac{N_{A2}}{G_1} + \frac{N_{A3}}{G_1 G_2}$$

$$F_{tot} = F_1 + \frac{F_2 - 1}{G_1}\frac{B_{2,3}}{B_{tot}} + \frac{F_3 - 1}{G_1 G_2}\frac{B_3}{B_{tot}}$$

Often, B is constant.

Department of Electronics and Nanoengineering
Kari Stadius, Saeed Naghavi, Jian Gao

Nonlinear Circuit

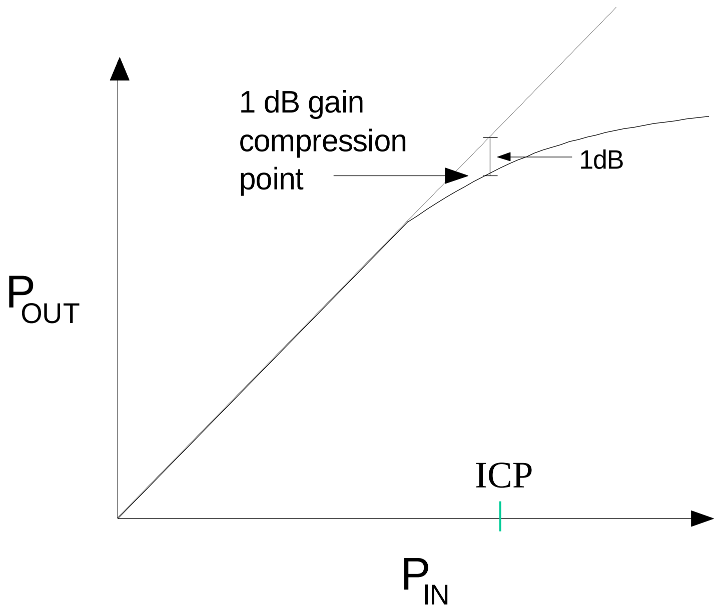
- Nonlinear circuit generates a series of new frequencies

- Widely used specifications
  - gain compression
  - distortion (level of harmonics)
  - intermodulation
  - blocker resilience

Gain Compression

- Consider a nonlinear circuit with 2nd and 3rd order nonlinearity

$$y(t) = \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t)$$



- Input $A\cos(\omega t) \rightarrow$ Output

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

- ICP = 1-dB gain compression point, referred to input $ICP = \sqrt{0.145\left|\frac{\alpha_1}{\alpha_3}\right|}$

Level of Harmonics

- Nonlinear circuit with 2nd and 3rd order nonlinearity

$$y(t) = \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t)$$

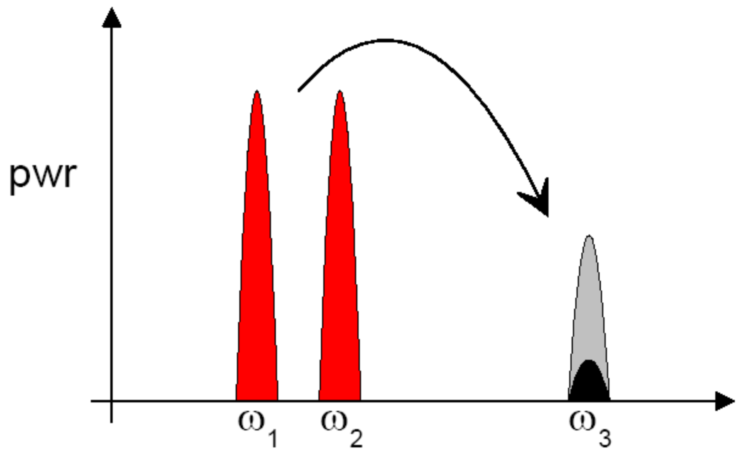
- Input Acos(ωt) → Output

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

- Power at harmonic frequencies is widely used measure (THD) in low-frequency circuits
- IN RF circuits this is often a problematic measure
  - RF circuits are often frequency selective
  - Harmonics can be at very high frequencies making measurements difficult

Intermodulation

- In wireless applications modulated narrow band signals are used
- Nonlinearities cause different frequency components to mix with each other resulting in spreading of the spectrum
- Mechanism causing the spread is called intermodulation distortion
- The two-tone test is a simplified test more suitable for testing and simulation



Intermodulation

- Nonlinear circuit with 2nd and 3rd order nonlinearity

$$y(t) = \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t)$$

- Input $A_1\cos(\omega_1 t) + A_2\cos(\omega_2 t) \rightarrow$ Output

$$v_{out}(t) = \frac{1}{2}\alpha_2\left(A_1^2 + A_2^2\right) + \left(\alpha_1 A_1 + \alpha_3 \frac{3A_1^3 + 6A_1A_2^2}{4}\right)\cos(\omega_1 t) + \left(\alpha_1 A_2 + \alpha_3 \frac{3A_2^3 + 6A_1^2A_2}{4}\right)\cos(\omega_2 t)$$

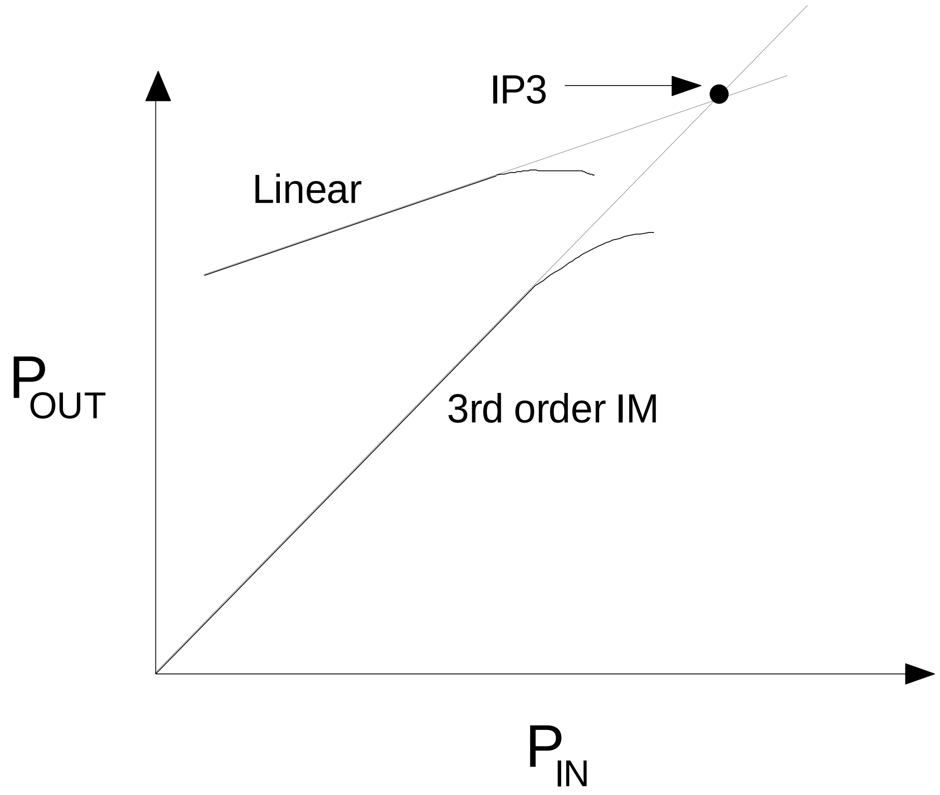
$$+ \tfrac{1}{2}\alpha_2 A_1^2\cos(2\omega_1 t) + \tfrac{1}{2}\alpha_2 A_2^2\cos(2\omega_2 t) + \tfrac{1}{4}\alpha_3 A_1^3\cos(3\omega_1 t) + \tfrac{1}{4}\alpha_3 A_2^3\cos(3\omega_2 t)$$

$$+ \alpha_2 A_1 A_2\left[\cos(\omega_1 t - \omega_2 t) + \cos(\omega_1 t + \omega_2 t)\right] + \tfrac{3}{4}\alpha_3 A_1^2 A_2\cos(2\omega_1 t + \omega_2 t) + \tfrac{3}{4}\alpha_3 A_1 A_2^2\cos(\omega_1 t + 2\omega_2 t)$$

$$+ \tfrac{3}{4}\alpha_3 A_1^2 A_2\cos(2\omega_1 t - \omega_2 t) + \tfrac{3}{4}\alpha_3 A_1 A_2^2\cos(2\omega_2 t - \omega_1 t)$$

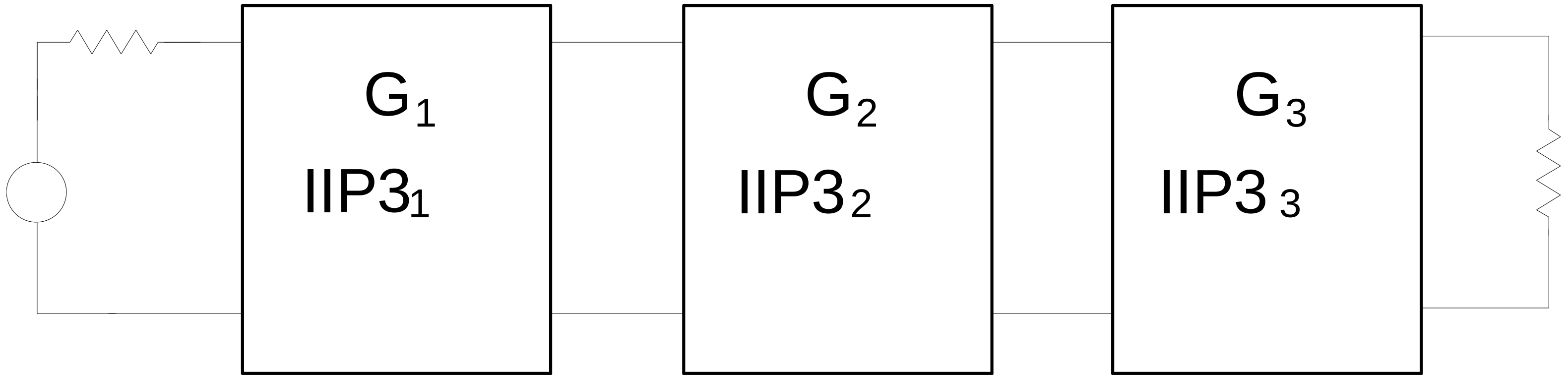
If ω_1 and ω_2 are close to each other then the third-order intermodulation products at $2\omega_1$-ω_2 and $2\omega_2$-ω_1 fall close to ω_1 and ω_2, and they appear at reception band.

3rd Order Intermodulation Intercept Point (IIP3, OIP3)



- IIP2 and IIP3 are measure of device's nonlinearity: $IIP2 = \left|\frac{\alpha_1}{\alpha_2}\right| \quad and \quad IIP3 = \sqrt{\frac{4}{3}\left|\frac{\alpha_1}{\alpha_3}\right|}$
- IIP3 – ICP = 10 dB under these assumptions

System IIP3



$$\boxed{\frac{1}{iip3_{tot}} = \frac{1}{iip3_1} + \frac{g_1}{iip3_{12}} + \frac{g_1 g_2}{iip3_3}}$$

There are filters in the system, particularly at base-band:

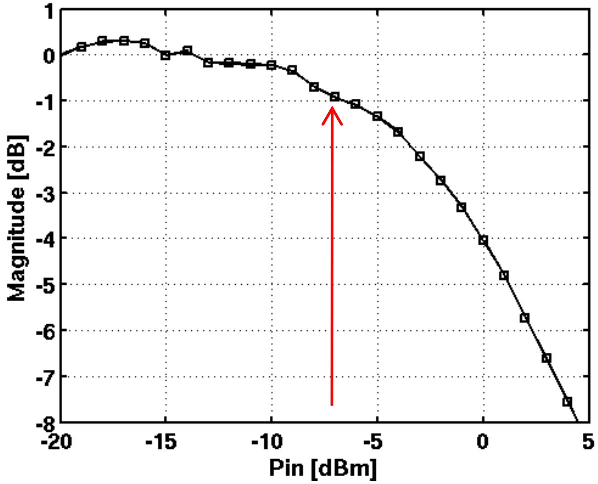
- **Out-of-band IIP3 = intermodulation products falls to the stop-band of BB**
- **In-band IIP3 = intermodulation products falls to the pass-band of BB**

Blocker Resilience

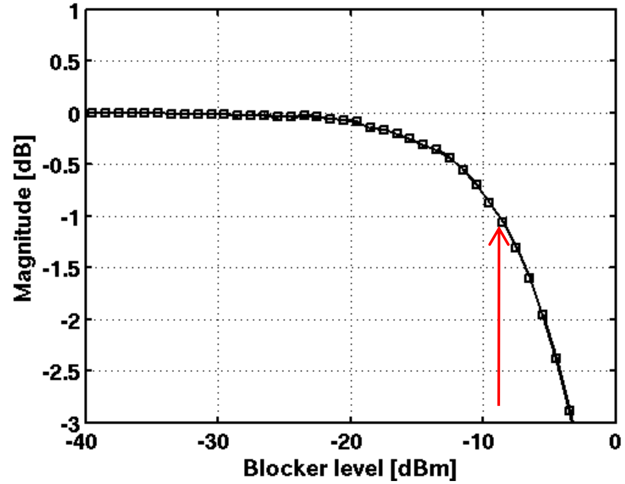
“Blocker”, “jammer” = A strong interfering signal that drives the receiver into / close to compression and the gain for the actual signal is reduced.

$$\frac{v_{out}}{v_{in}} \approx \alpha_1\left(1+\frac{3}{2}\frac{\alpha_3}{\alpha_1}A_2^2\right)$$

(A_2 is the blocker, α_3 is negative)

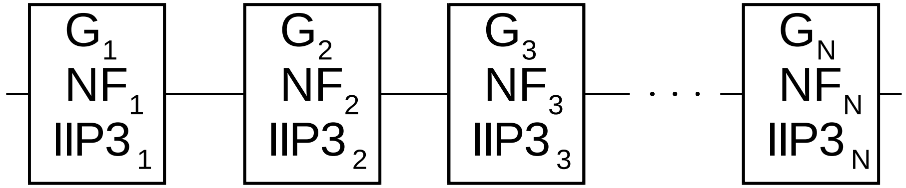


Measured input-referred gain compression (ICP) at 2.4 GHz (relative to 31dB level)



Measured gain desensitization (relative to 31dB level). Here the actual signal is at 2.0 GHz and the blocker signal is at 2.4 GHz

Chain Calculations



$$G_{TOTAL} = \prod_{k=1}^{N} G_k$$

$$F_{TOTAL} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \ldots + \frac{F_N - 1}{G_1 G_2 \ldots G_{N-1}}$$

$$\frac{1}{IIP3_{TOTAL}} \approx \frac{1}{IIP3_1} + \frac{G_1}{IIP3_2} + \frac{G_1 G_2}{IIP3_3} + \ldots + \frac{G_1 G_2 \ldots G_{N-1}}{IIP3_N}$$

- NF of first stages dominate
- IIP3 requirement increases along the chain
- NF of attenuator: NF=ATT
- Assumption: power matched blocks, not exact for RF IC

Self-Learning Assignment 1

Objectives are to familiarize yourself with

- typical textbook level material on radio transceivers
- concepts
- architectures
- Aalto Library ebook-collections

You can find the assignment from

MyCourses / Assignments - SLA / Self-learning assignment 1

Return your answer as a pdf-file to Return Box in the same page

Next Meeting

Topics will be

- RF IC technologies
- High frequency properties of integrated devices
- RF IC specific devices: inductors and RF capacitors

This meeting will continue with

advices on homeworks and CAD exercise

at **14:15**