Wireless Transceiver Electronics
(WTE)

Course # 2/9

RF transceiver systems & Terminology

121150

Content lecture # 2/9

RF transceiver systems

- Introduction
- Basic RX functionality
- Basic TX functionality

RF Terminology

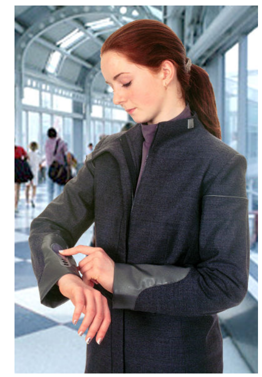
- Gain
- Noise
- Non-linearity
- Sensitivity
- Cascading of sub-systems and SFDR

Introduction

Origin of all specifications: applications

High bit-rate wireless networks

Bluetooth, hyperlan, HomeRF



Low bit-rate wireless connection

Wearable electronics, sensor data transfer

Cellular communication

Dect, GSM, third generation (UMTS,..)

Optical Networks

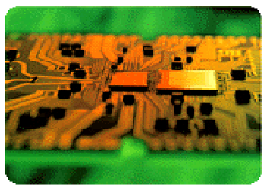
Sonet / SDH/
burst-mode

etcetera, etcetera

From system to RF spec.

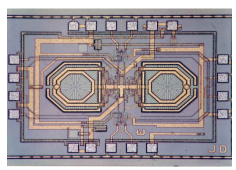
Applications

System spec.



Systems / building blocks

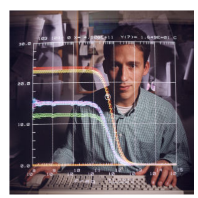
RF spec.



Integrated (RF) circuits

which you are designing

Technology spec.



IC technology

Different applications: different specifications (of course.. but can be a lot different)

For example:

Portable applications

Mains supplied applications

or

Consumer applications

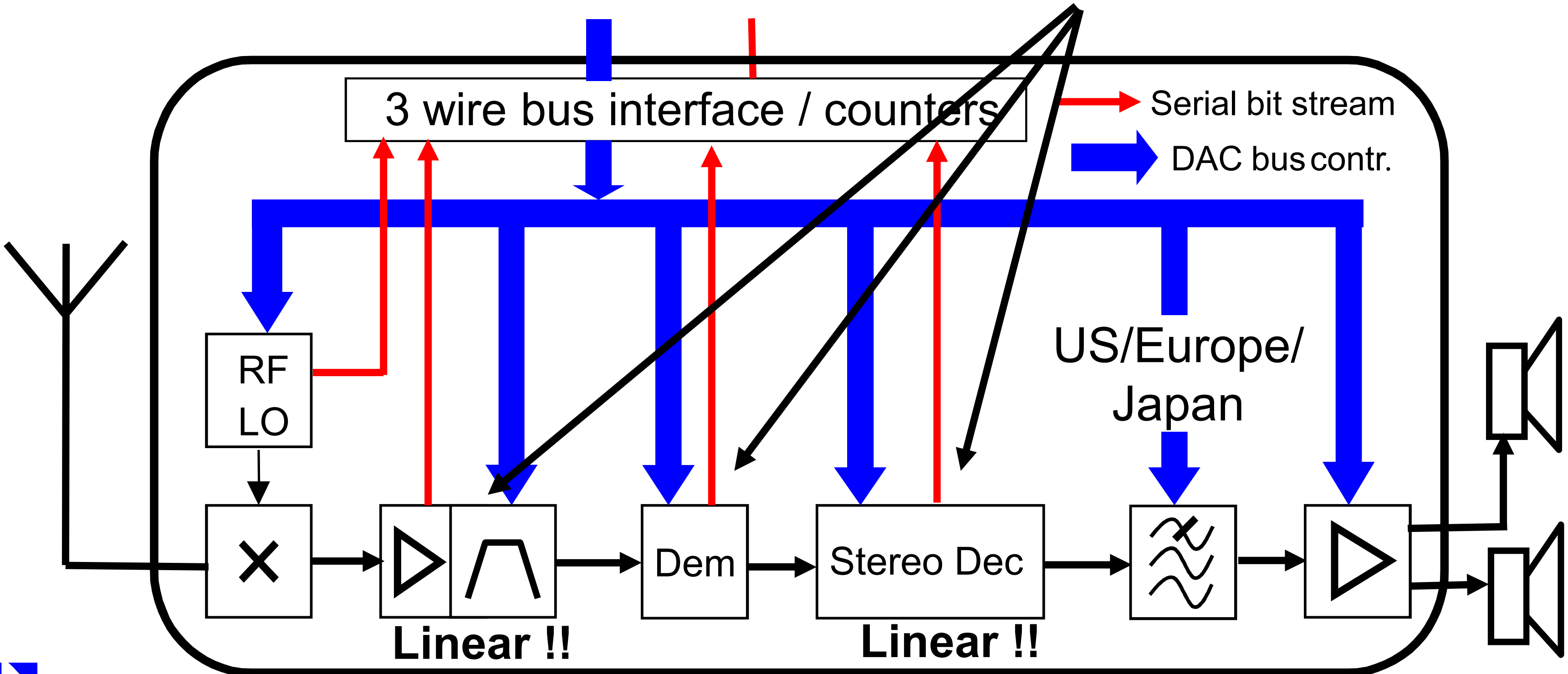
Professional applications

- *chip area*
- *cost*
- *power*
- *features*

priority order chances for all four types of applications….

From system to RF Spec. and RF building block specifications

First the system specification has to be translated into RF specification (e.g. sensitivity to noise figure). Next the RF specification must be transformed into RF building block spec.



RF transceiver design parameters

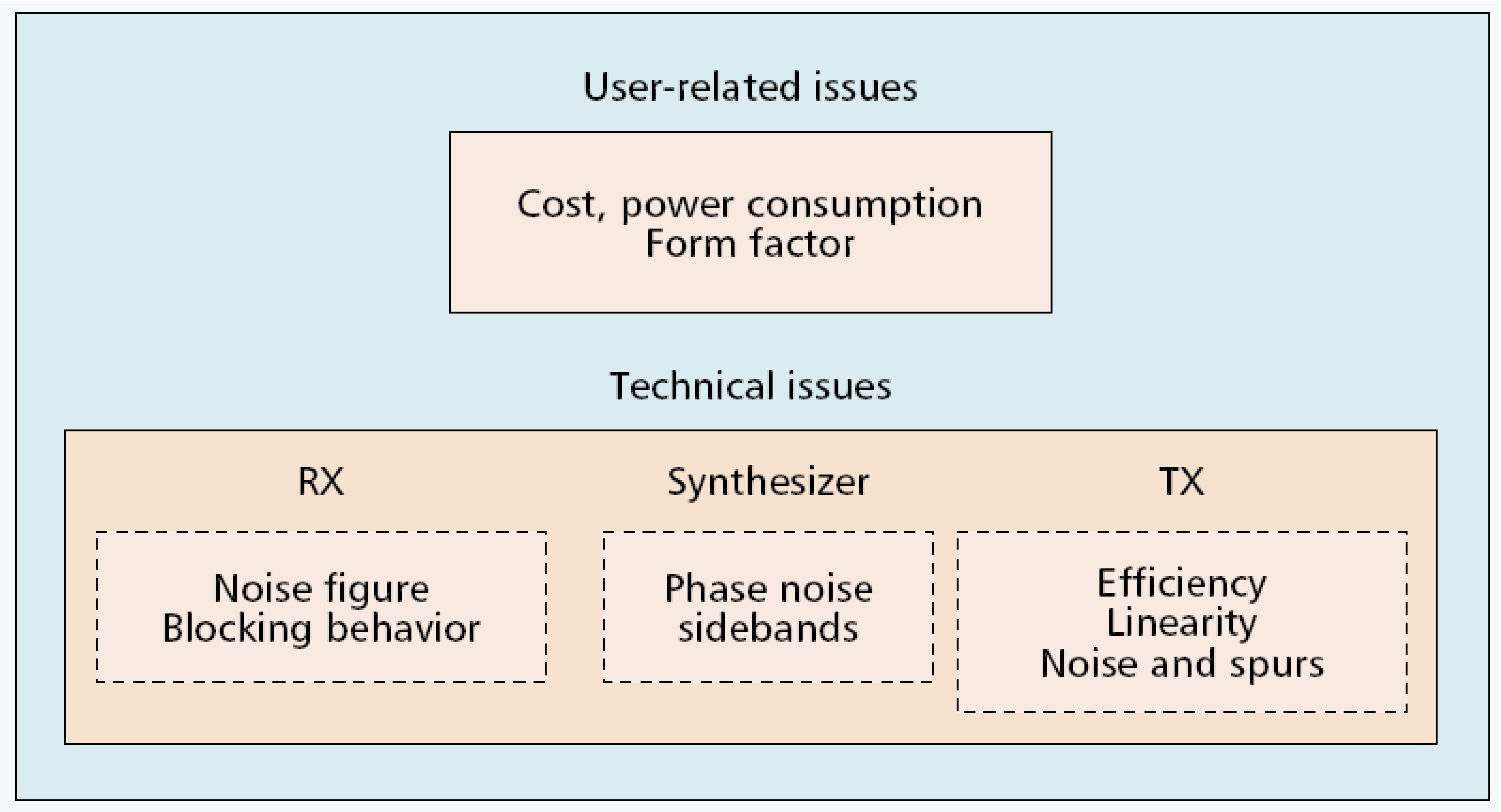
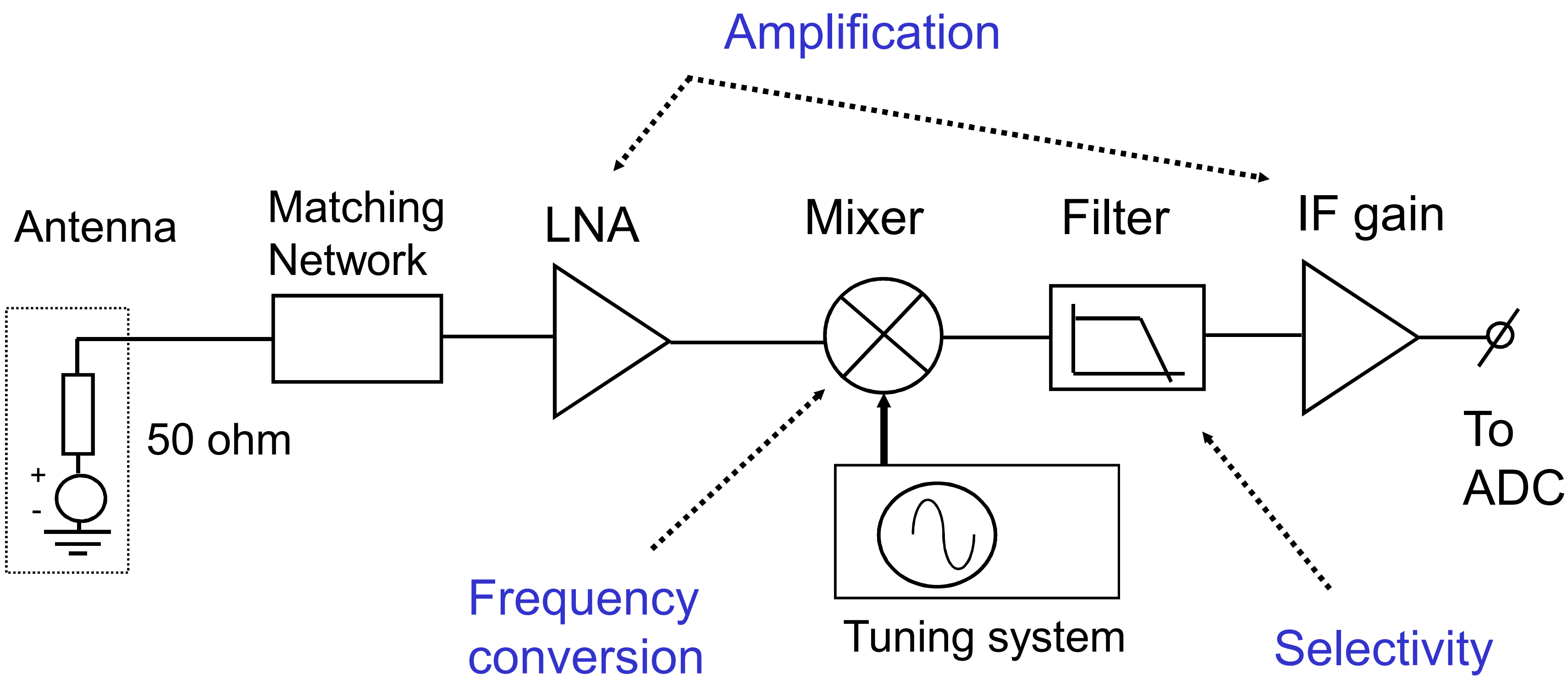
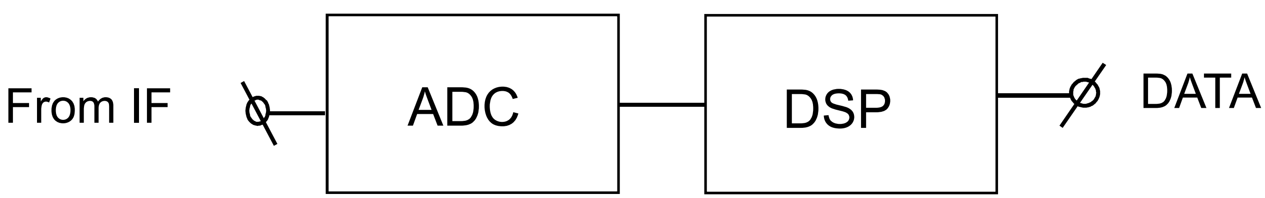


Image: B. Razavi

Basic RX functionality

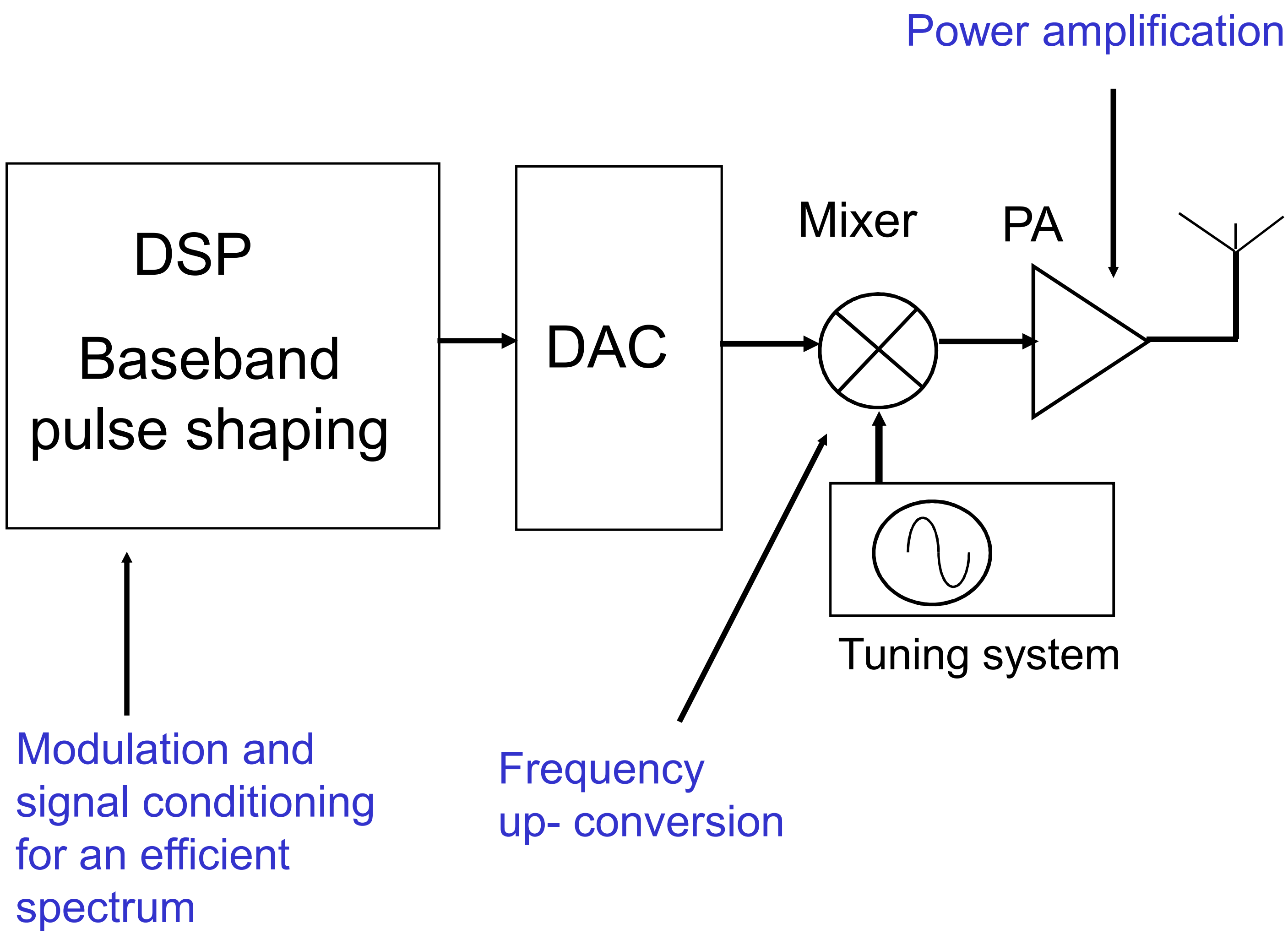
Most important functions of a receiver (RX)



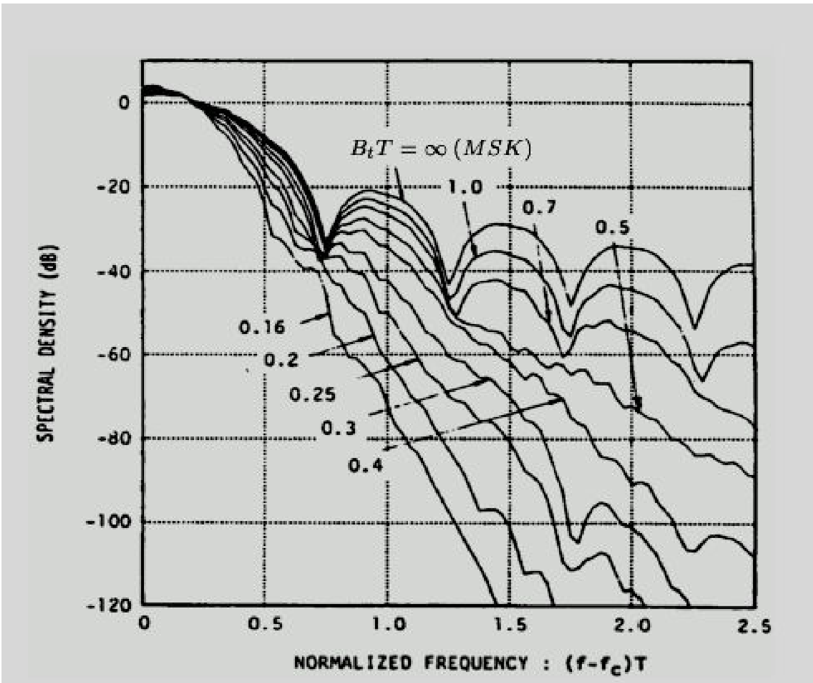


Basic TX functionality

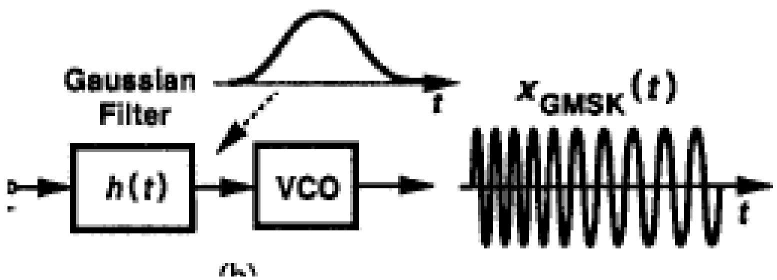
Most important functions of a transmitter (TX)



For example, BPSK occupies a relatively large spectrum.



GMSK (Gaussian minimum shift keying) makes use of a pulse shaping filter to limit the spectral content.



$$h_G(t) = B_t \frac{2\pi}{\ln 2}\, e^{-\frac{2\pi^2 B_t^2}{\ln 2} t^2}$$

3 dB bandwidth of Gaussian LPF filter.

Image: B. Razavi, V. Vidojkovic

RF system specifications

Start your design always with well-defined ***specifications***

If you don’t know what you want
it is
(very) ***unlikely***
that you get what you want

Definitions of dB and dBm

A (power) ratio can be expressed in decibels (dBs) as:

$$10 \, Log \, (P_1/P_2) \, dB$$

A voltage ratio can be expressed in dBs as:

$$20 \, Log \, (V_1/V_2) \, dB$$

The power in dBm is defined as:

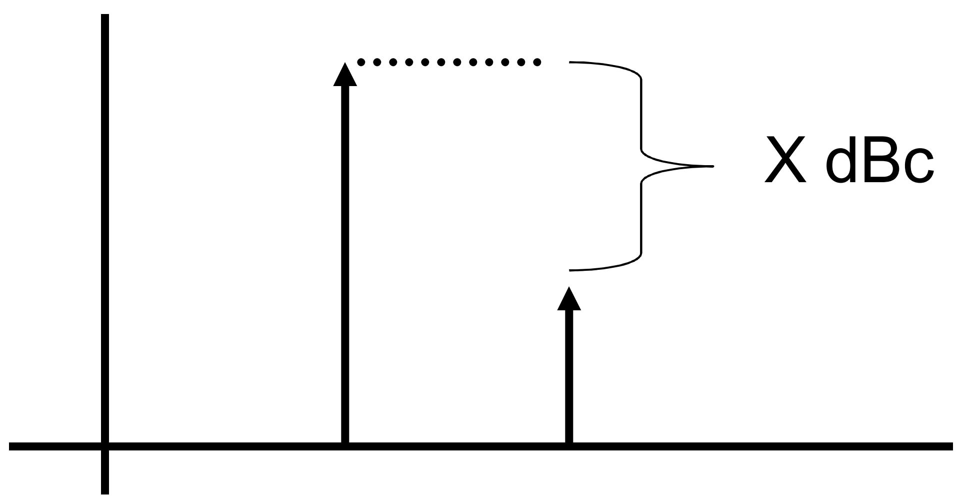
$10 \, Log \, (P/1mW)$, and (normally) with $P=V_{rms}^2/50 \, ohm$

Some dBm and equivalent mV-values in 50 ohm

-20 dBm →	22.3 mV_{rms}
-10 dBm →	70.7 mV_{rms}
0 dBm →	223.6 mV_{rms}
+10 dBm →	707.1 mV_{rms}

Definition of dBc

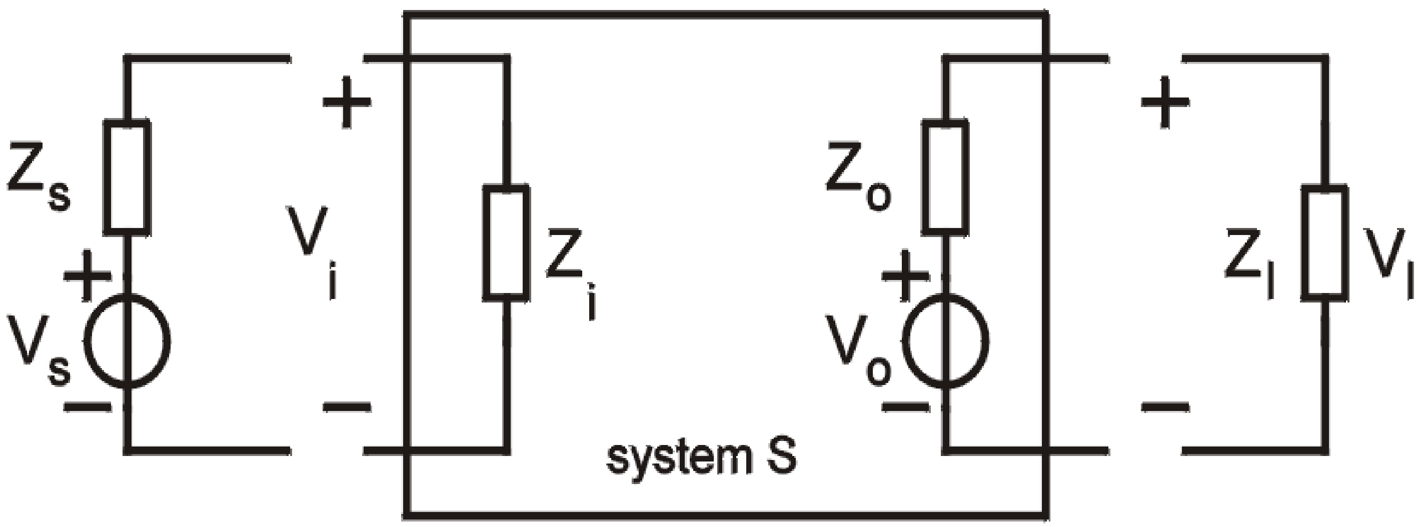
dBc is referring to dB relative to a carrier (hence the c), fundamental or other signal:



For example: harmonics relative to a fundamental

GAIN

Gain: system model



Time-invariant system S with load impedance Z_l . System S has an input impedance Z_i and an output impedance Z_o

Meaning of the word gain

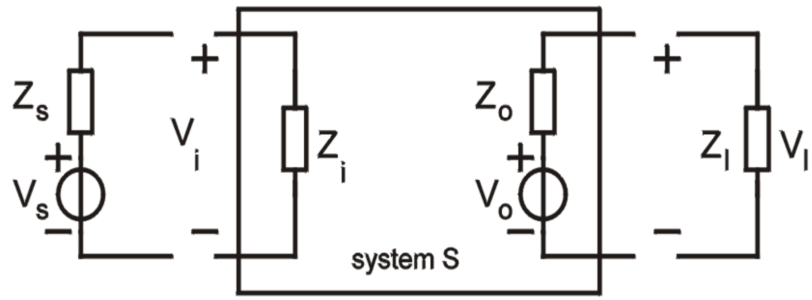
Means nothing without the correct additional specifications:

- *What is the load / source impedance*
- *Voltage or power gain, and which power gain?*

Analog designers normally use the definition of voltage gain.

RF / microwave designers are more familiar with several gain definitions in terms of power.

Voltage gain

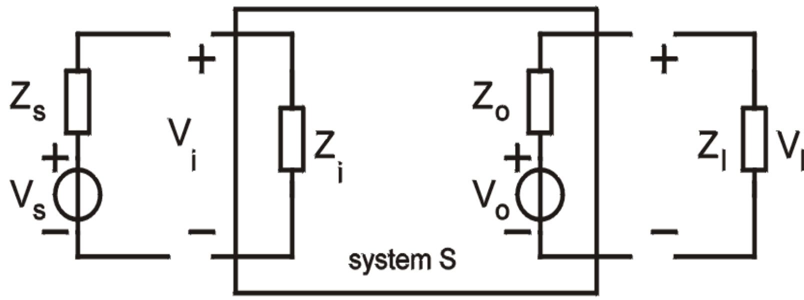


unloaded

$$A_v = \frac{V_o}{V_i} \rightarrow \frac{V_l}{V_s}$$

Assuming Z_i is much higher (i.e. $Z_i \rightarrow \infty$) than Z_s and Z_o is much smaller (i.e. $Z_o \rightarrow 0$) than Z_l. In the limiting case no current is flowing into system S.

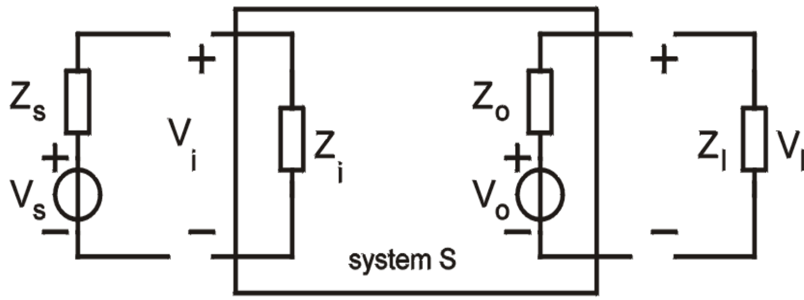
Delivered power at the input



$$P_{i,del} = \frac{V_i^2}{R_i} = \frac{R_i}{(R_i + R_s)^2} \cdot V_s^2$$

This is the power delivered at the input of system S. (Treating the impedances Z as resistors).

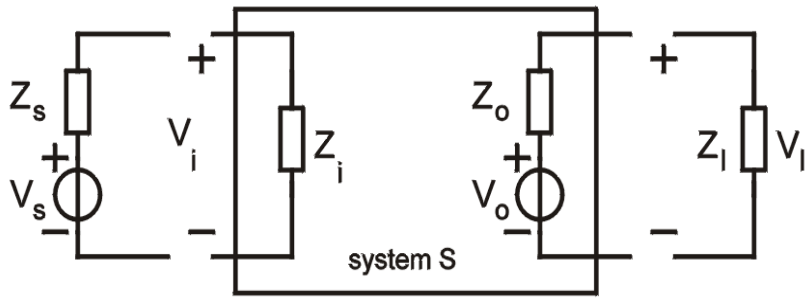
Available power at the input



$$P_{s,av} = \frac{V_s^2}{4R_s}$$

Maximum power that can be delivered to the input of the system S: $Z_s = Z_i^*$ (conjugate input match).

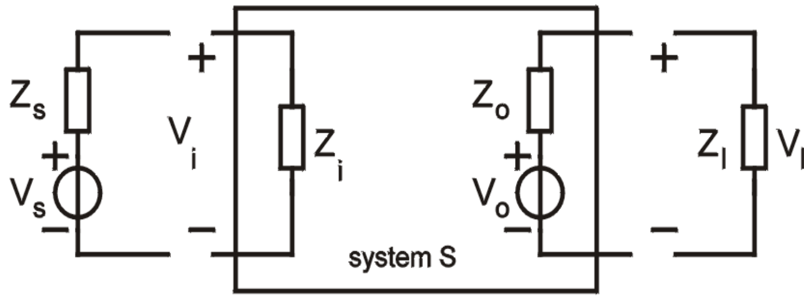
Available power at the output



$$P_{o,av} = \frac{V_o^2}{4R_o} = \left(\frac{R_i}{R_i + R_s}\right)^2 V_s^2 A_v^2 \frac{1}{4R_o}$$

Maximum power that can be delivered to the output of the system S: $Z_o = Z_l^*$ (conjugate output match).

Available gain G_a



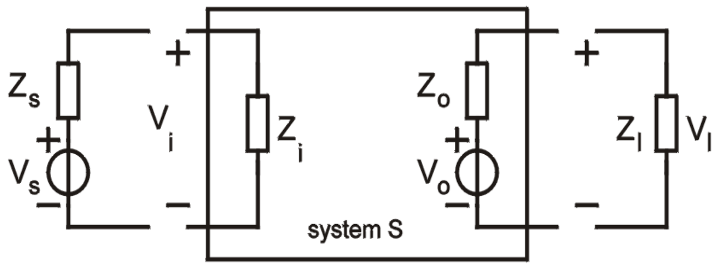
$$G_a = \frac{P_{o,av}}{P_{s,av}} = \left(\frac{R_i}{R_i + R_s}\right)^2 A_v^2 \frac{R_s}{R_o} < \frac{P_{o,av}}{P_{i,del}}$$

Mismatch between R_i and R_s reduced G_a. A perfect input match yields $P_{s,av} = P_{i,del}$. G_a assumes a perfect output match.

Calculation example

$$A_v = \frac{V_o}{V_i}$$

$$G_a = \frac{P_{o,av}}{P_{s,av}} = \left(\frac{R_i}{R_i + R_s}\right)^2 A_v^2 \frac{R_s}{R_o}$$



Suppose: Av=10, Ro,Rs, Ri=50 Ohm

20*log(A_v/2)=14 dB

10*log(Ga)=14 dB

Output voltage division

Conclusion: in a matched system: Ga en squared **loaded** voltage gain are equal. Ga is convinient in a matched system: no knowledge of impedance levels needed.

NOISE

Noise Figure

One of the most important parameters in analog and RF circuit design is the Signal to Noise Ratio (SNR)

The noise factor of a system S is defined as:

$$F = \frac{SNR_{at\ the\ input\ of\ S}}{SNR_{at\ the\ output\ of\ S}}$$

The noise figure (NF) of a system is simply *10 Log (F)* in dB.

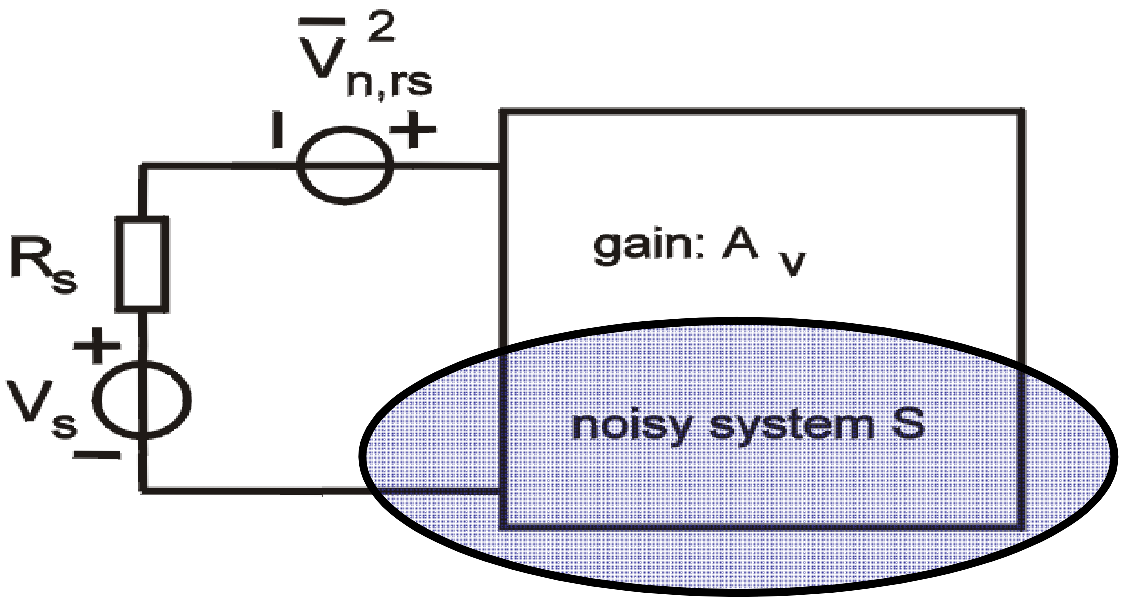
F in terms of N, G_a and P_{in}

$$F = \frac{SNR_{\text{at the input of S}}}{SNR_{\text{at the output of S}}}$$

$$= \frac{P_{in} N_{out}}{G_a P_{in} N_{in}} = \frac{N_{out}}{G_a N_{in}}$$

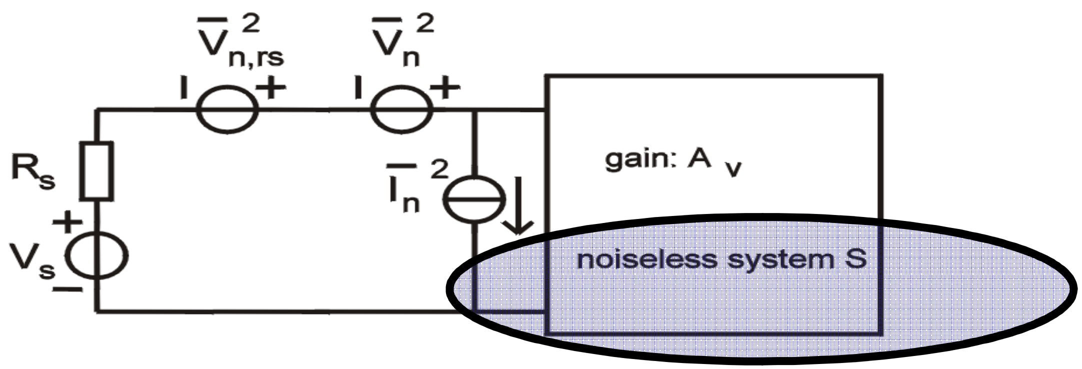
With N_{out}, the total noise at the output. The noise factor is a measure of how much the SNR degrades as the signal passes through a system / RF building block.

Calculation of input referred noise (I)



$V^2_{n,rs} = 4\ kTR_s * df$: single-sided thermal noise power spectral density, with k Boltzmann's constant and T the absolute temperature. (density: so time BW for power if white.)

Calculation of input referred noise (II)



$$F = 1 + \frac{\overline{(V_n + R_s I_n)^2}}{\overline{V_{n,rs}^2}}$$

When F is taken in 1 Hz:
spot noise figure

V_n and I_n are added before squaring: to take (possible) correlation into account. When $R_s \rightarrow 0$, I_n can be neglected. When $R_s \rightarrow \infty$, V_n can be neglected.

Noise calculations in general

Add noise powers

Hence:

$$V_{n,total} = \sqrt{\overline{V_{n,1}^2} + \overline{V_{n,2}^2} + \ldots}$$

Use squared transfer function:

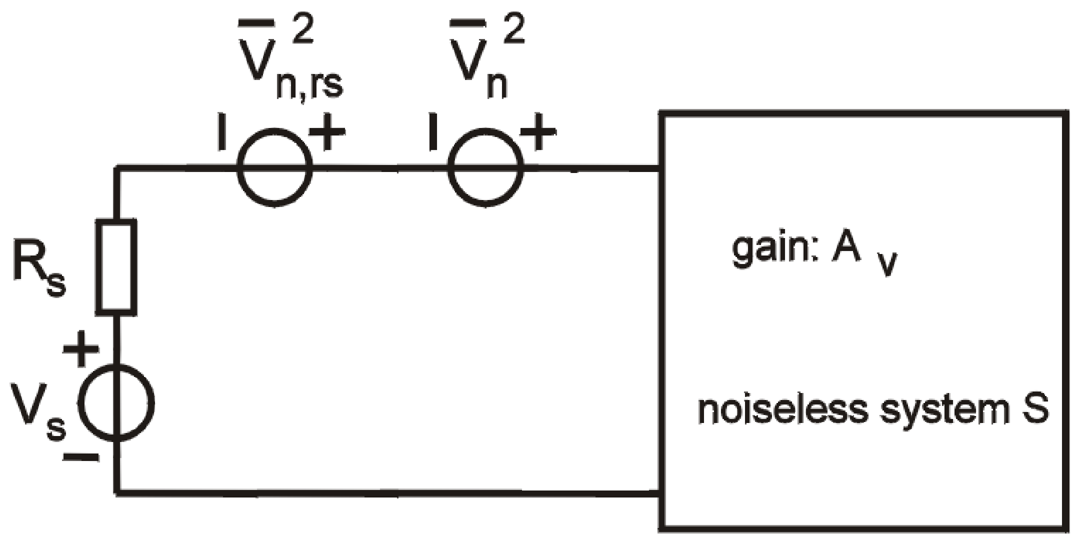
$$\overline{V_{n,out}^2} = \overline{V_{n,in}^2} * \left|H(f)\right|^2$$

As F is dependent on the source impedance: minimization of F for a given two-port system is possible for a proper value of the source resistance $R_{s:}$

Optimal Noise match

The source resistance for which F is minimum (Z_s=Z_{opt}), is normally not the same as the source resistance for maximum power transfer: Z_s=Z_{in}*

Quick noise assesment



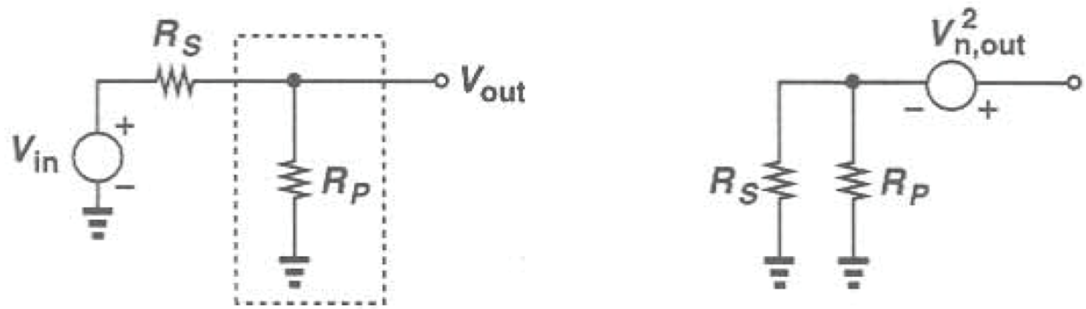
If V_n is dominant (no signficant I_n) and can be written as 4 KTR_{nv}* dF (equivalent noise resistance)

Then:

$$F = 1 + \frac{R_{nv}}{R_s}$$

For equal R values: F = 3 dB, the circuit produces the same amount of noise as the source resistance.

Calculation example



$$V^2_{n,out} = 4kT(R_S||R_P),$$

$$A_v = \frac{R_P}{R_S + R_P}$$

$$NF = \frac{V^2_{n,out}}{A^2}\frac{1}{4kTR_S} =$$

$$NF = 4kT(R_S||R_P)\frac{(R_S+R_P)^2}{R_P^2}\frac{1}{4kTR_S}$$

$$= 1 + \frac{R_S}{R_P}.$$

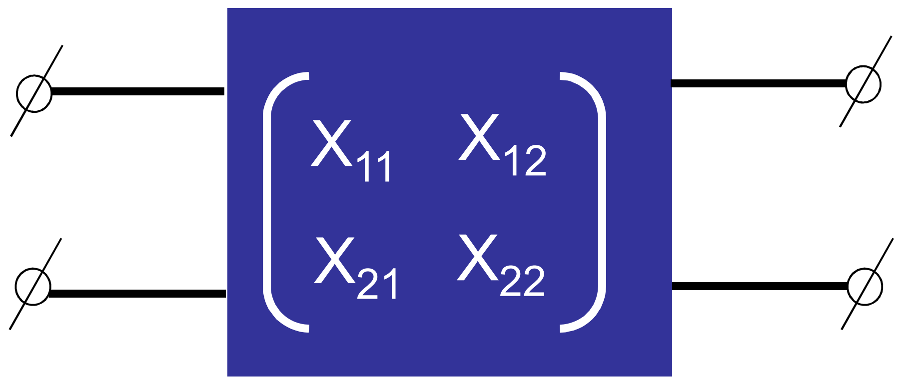
Maximize R_p to minimize NF : not equal to maximum power transfer (R_s=R_p)

Source:Razavi

NON-LINEARITY

Characterization of linear systems

Linear
two-port:

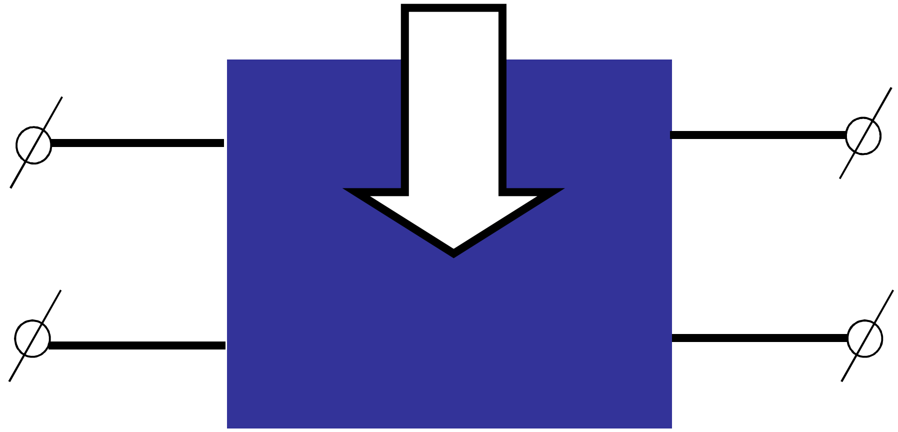


Complete description using Z, Y, H, transmission (ABCD), or S parameters

However, most practical systems are non-linear to a small or large extend

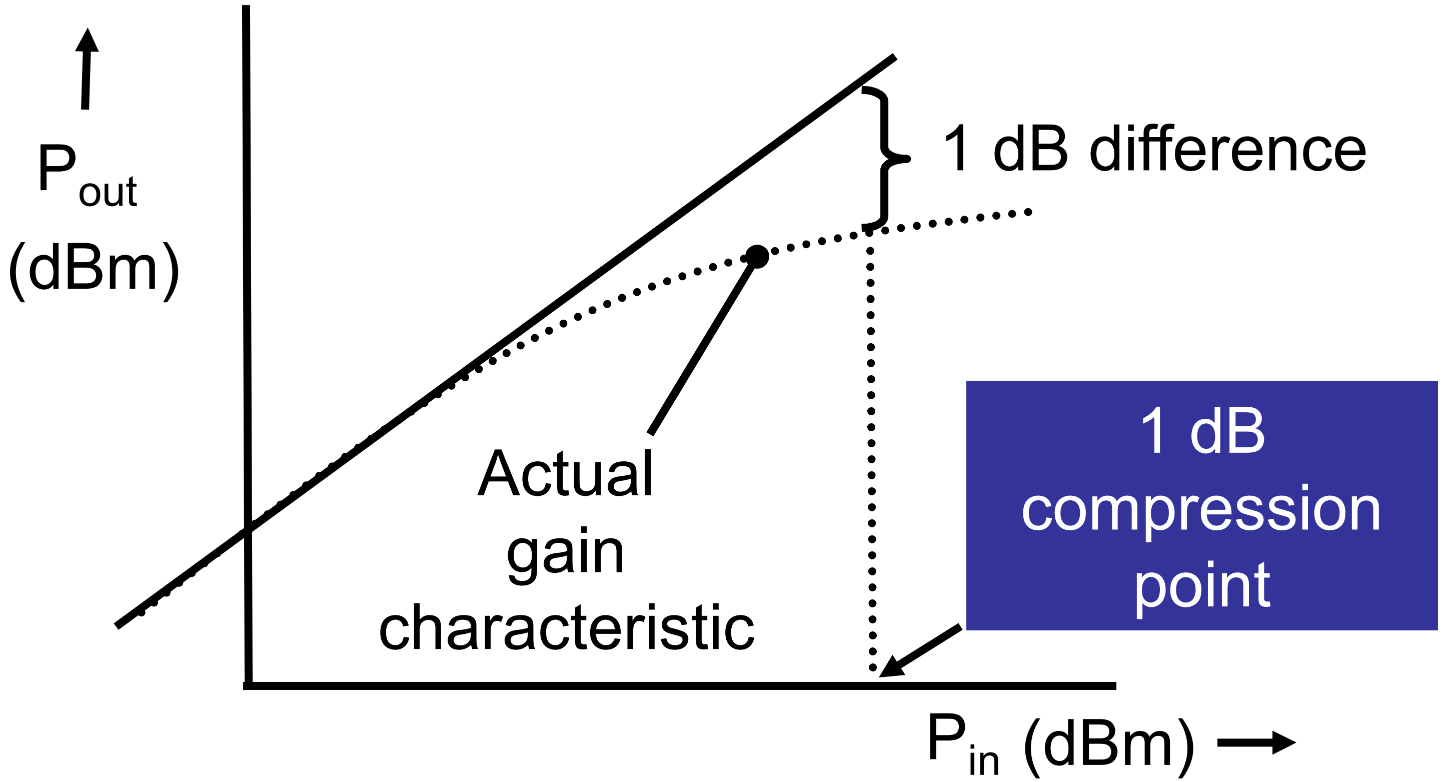
Practical systems:

$$y(t) = \alpha_0 + \alpha_1 \cdot x(t) + \alpha_2 \cdot x^2(t) + \alpha_3 \cdot x^3(t) + \ldots$$



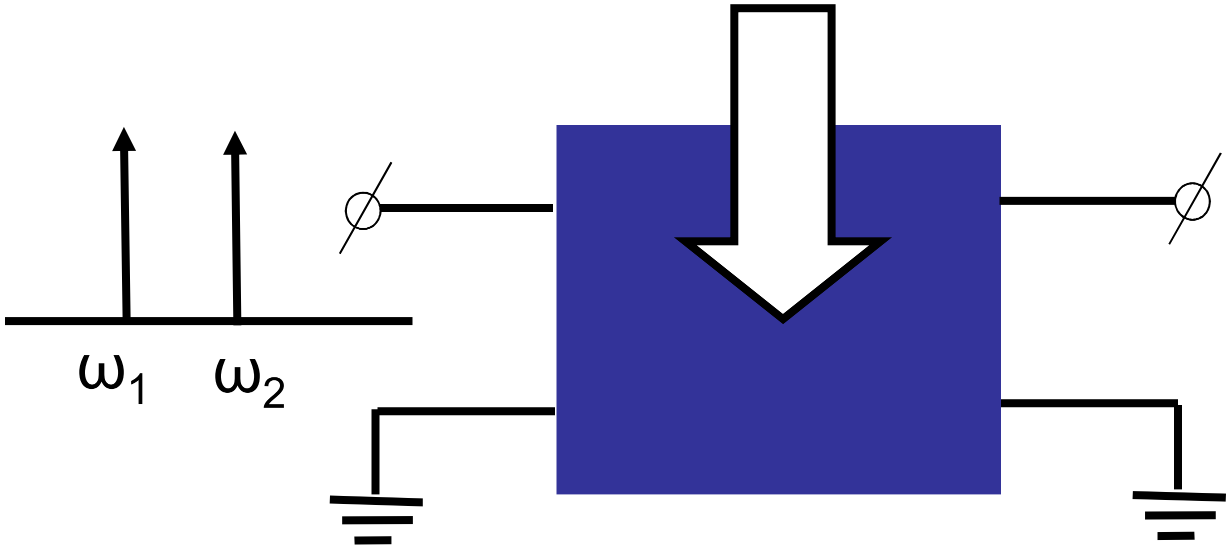
Have a non-linear transfer function; hence when a sine wave passes through the system harmonics will be generated.

1 dB compression point



Two signals at the input of a non-linear system

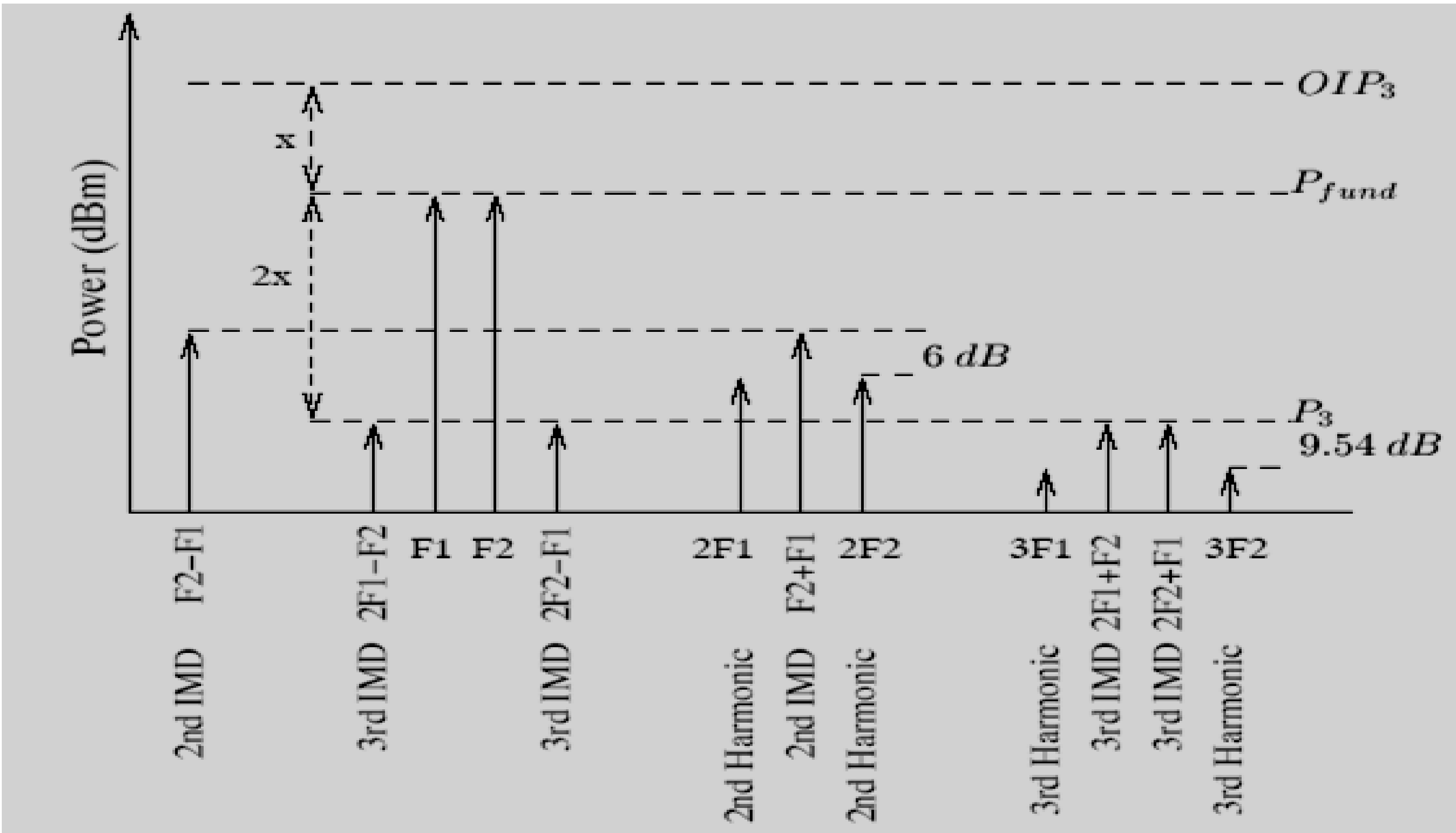
$$y(t) = \alpha_0 + \alpha_1 \cdot x(t) + \alpha_2 \cdot x^2(t) + \alpha_3 \cdot x^3(t) + \ldots$$



Yield a lot! of other frequency components

$$x(t) = A_1 \cos(\omega_1 t) + A_2 \cos(\omega_2 t)$$

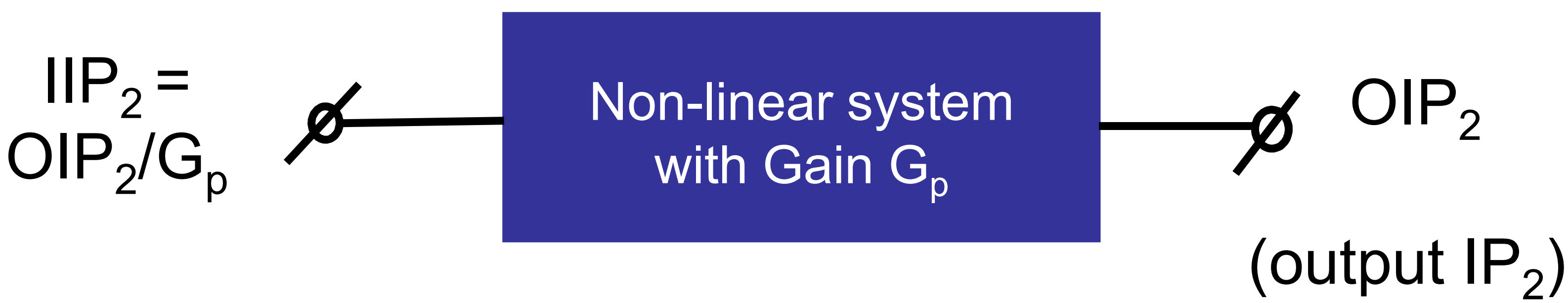
Graphical overview of inter-modulation products



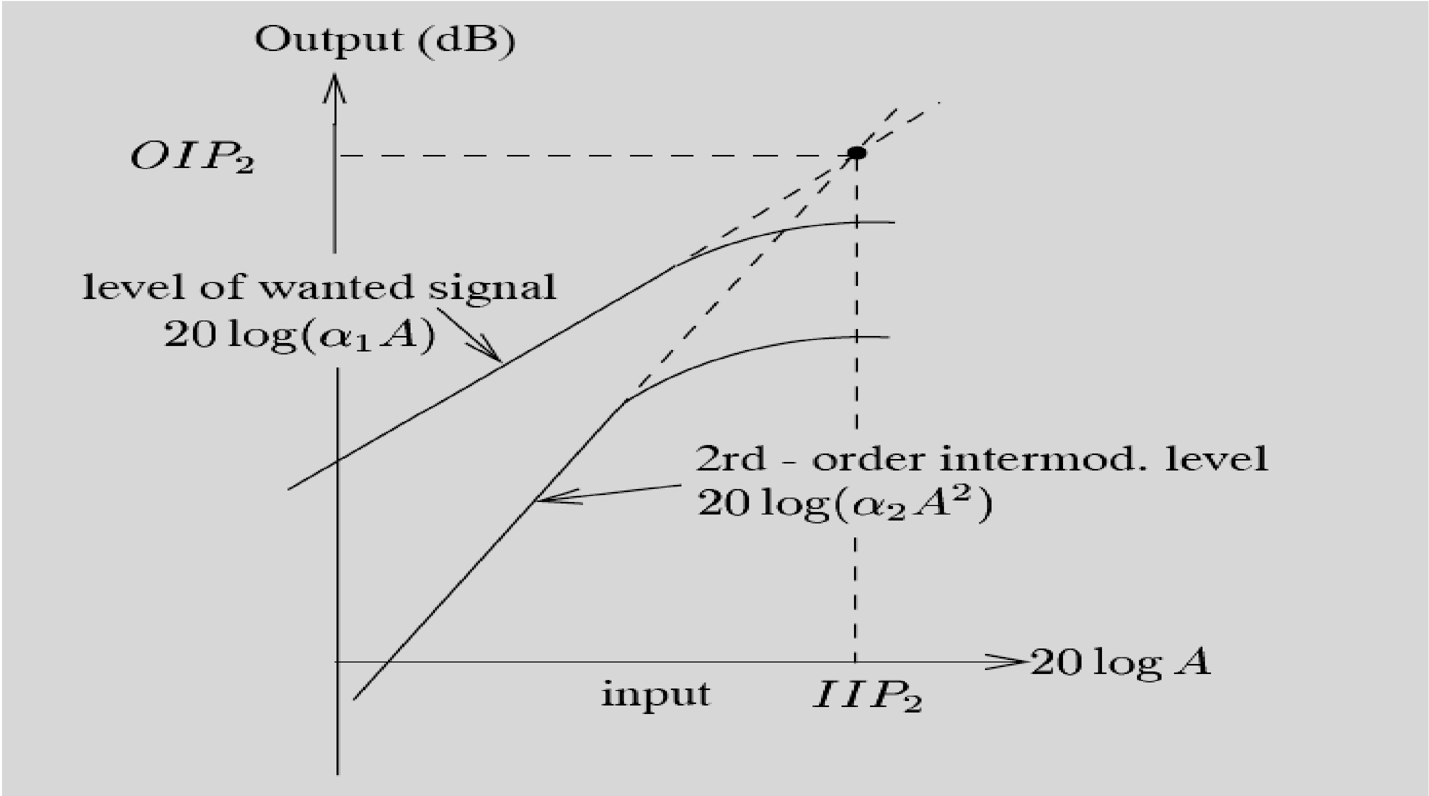
The second order intercept point is abbreviated as IP2.

$$y(t) = \alpha_0 + \alpha_1 \cdot x(t) + \alpha_2 \cdot x^2(t) + \alpha_3 \cdot x^3(t) + \ldots$$

IP2 is the characterization of α_2

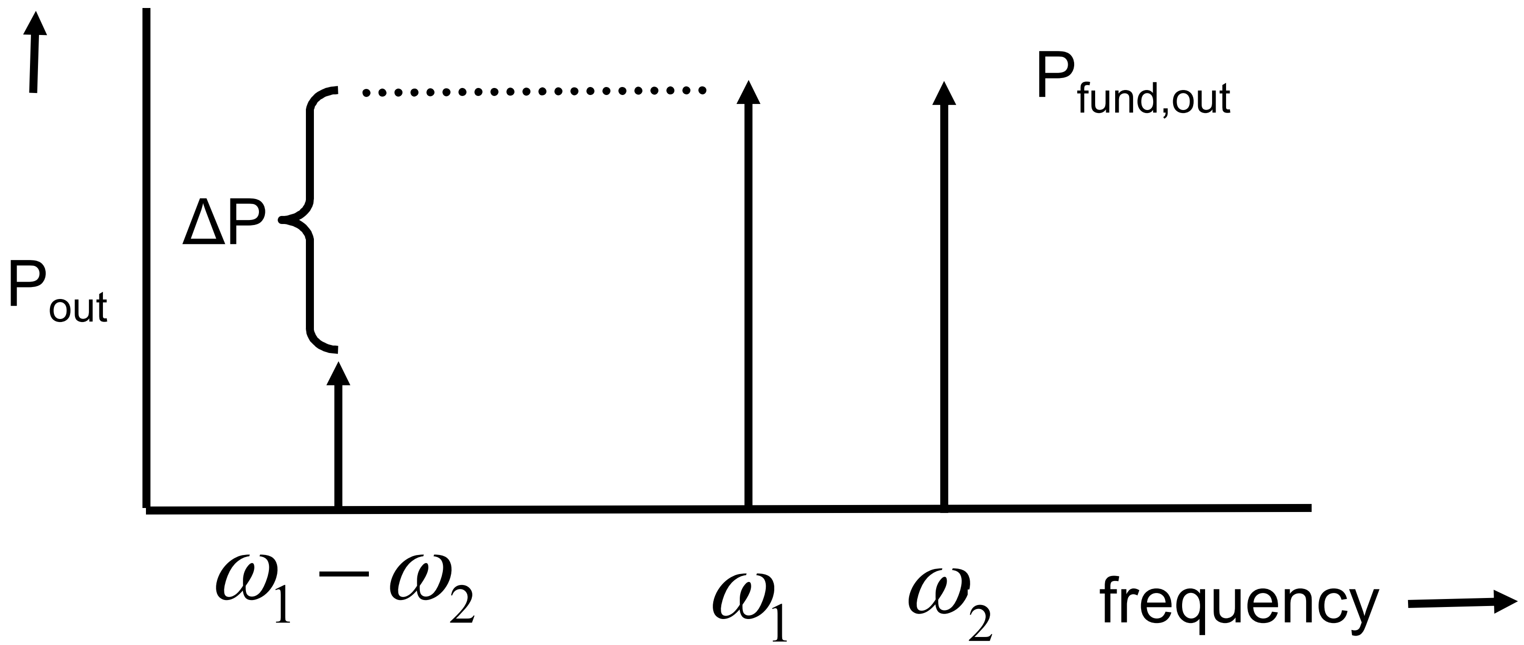


Calculation of IP2



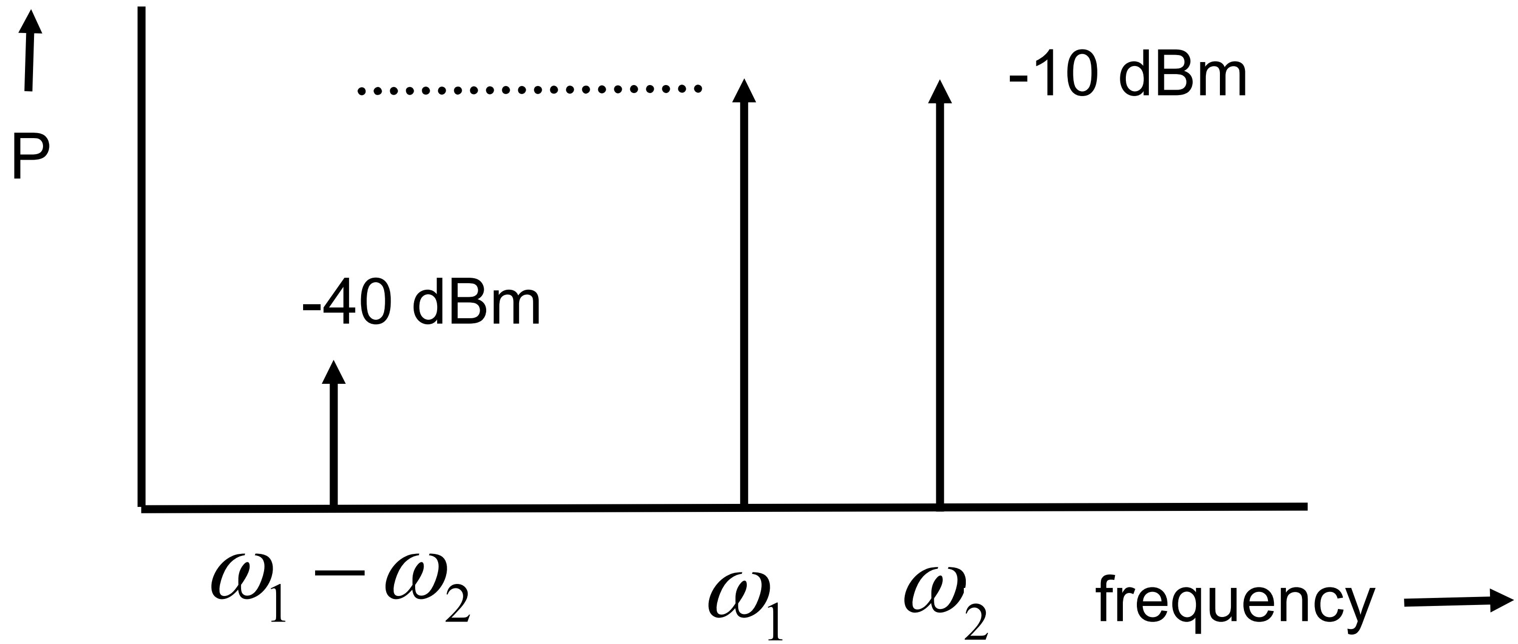
The IIP2 is the input power where the wanted signal and the second order intermodulation signal are equal (extrapolated point).

Formula for OIP2 (when not in compression)



$$OIP_2 = P_{fund,out} + \Delta P$$ (dBm)

Calculation example



What is IIP2 and OIP2 assuming a power gain of 7 dB

$$OIP_2 = P_{fund,out} + \Delta P = -10 + 30 = +20dBm$$

The input IIP2 is OIP2 divided by the power gain (so -7 dB)

IP2 important for:

Wideband (more than on octave) systems

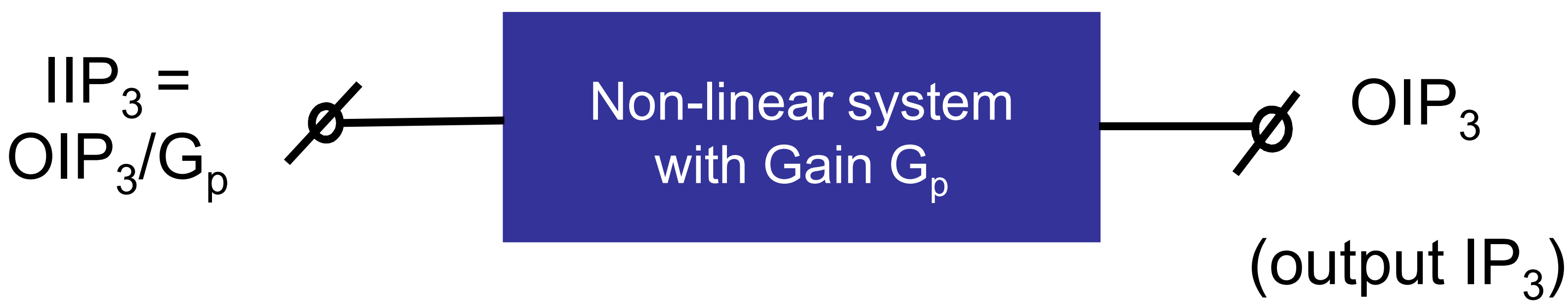
Low-IF receivers

Zero-IF receivers

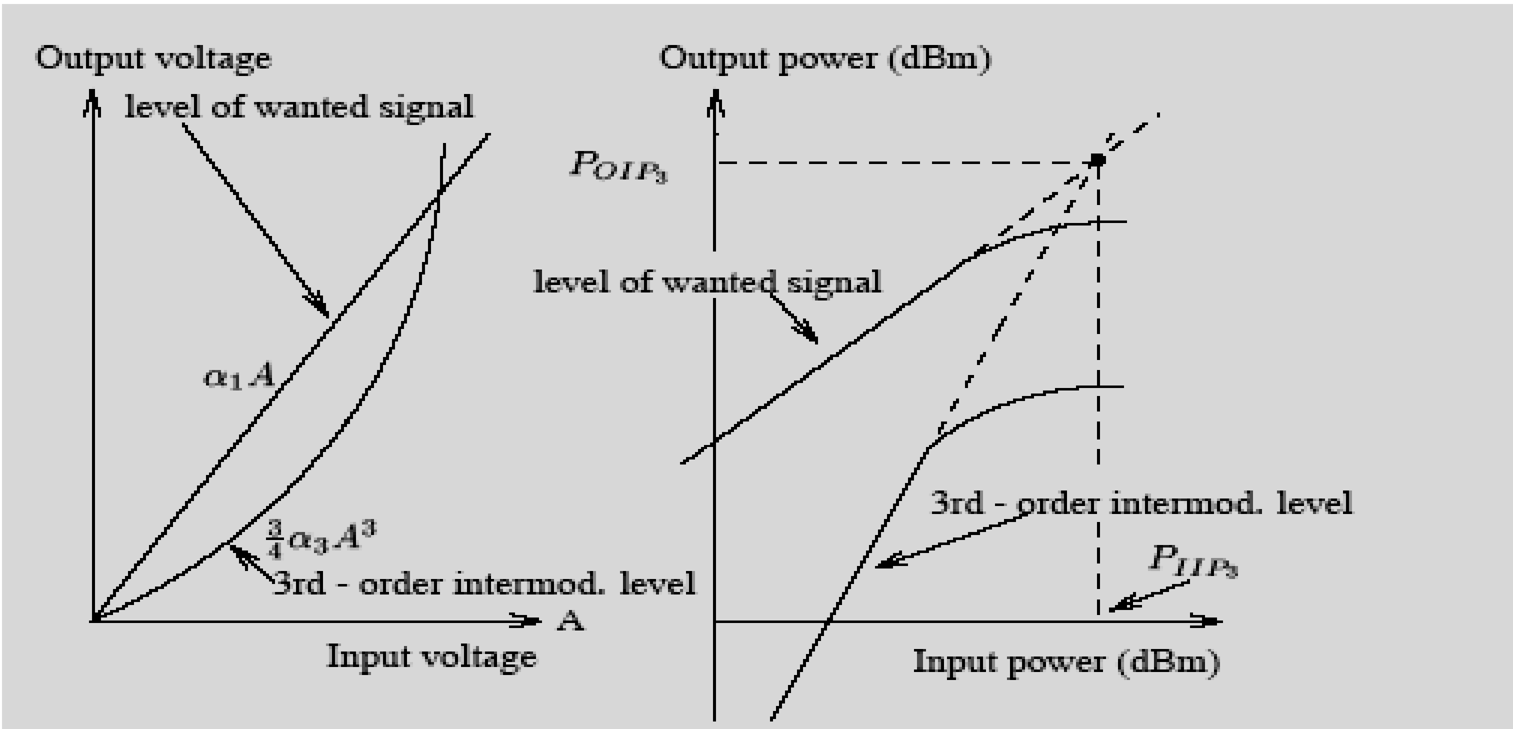
The third order intercept point is abbreviated as IP3.

$$y(t) = \alpha_0 + \alpha_1 \cdot x(t) + \alpha_2 \cdot x^2(t) + \alpha_3 \cdot x^3(t) + \ldots$$

IP3 is the characterization of α_3

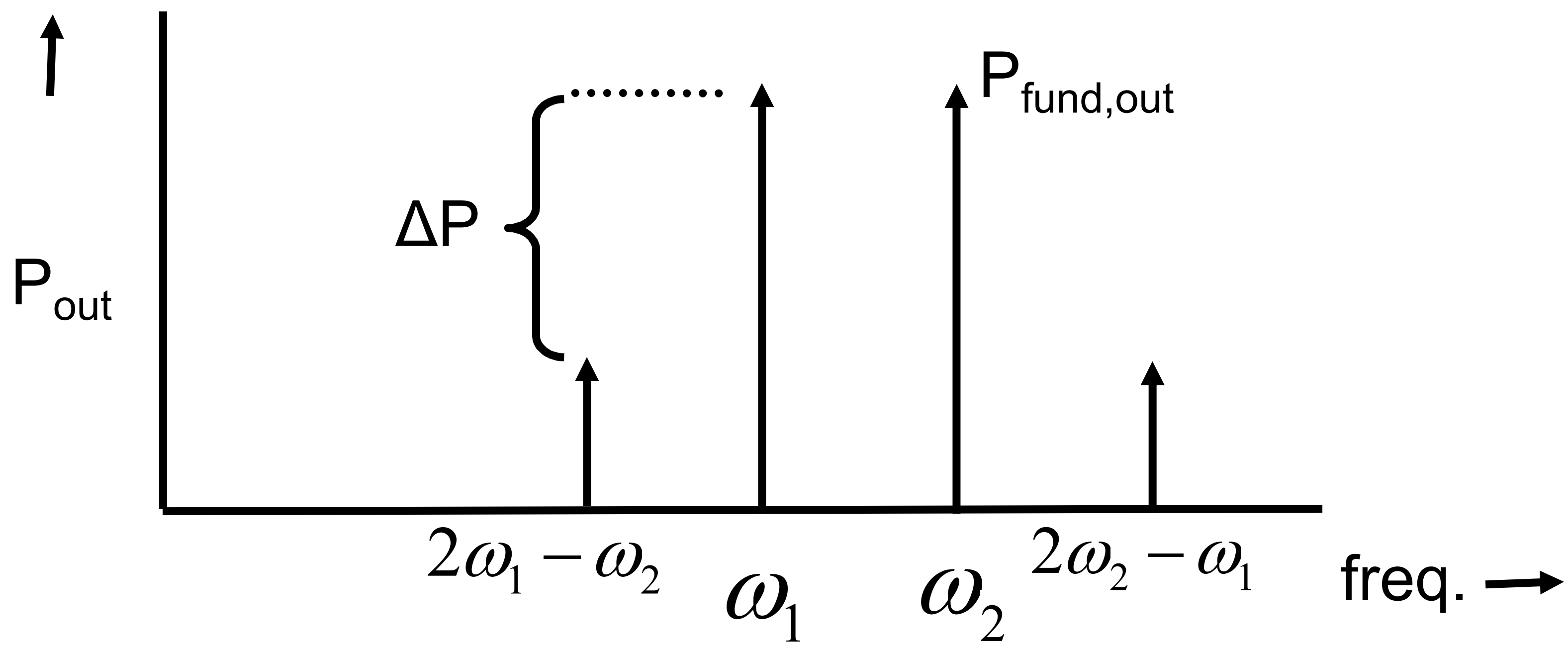


Calculation of IP3



The IIP3 is the input power where the wanted signal and the third order intermodulation signal are equal (extrapolated point).

Formula for OIP3 (when not in compression)



$$OIP_3 = P_{fund,out} + \frac{\Delta P}{2}$$ (dBm)

IP3 important for:

For any narrow and wideband system (blocking, in-band IM3 (third order inter-modulation component)

N^{th}-order intermodulation point

The n-th order (input) intercept point is related to the n-th order intermodulation signal and can be calculated with:

$$IIP_n = P_{fund,in} + \frac{\Delta P}{(n-1)} \quad \text{(dBm)}$$

Checks out, see for example IIP3 (same formula for output IP_n (OIP_n): but then use $P_{fund,out}$ instead of $P_{fund,in}$

$$IIP_3 = P_{fund,in} + \frac{\Delta P}{2} \quad \text{(dBm)}$$

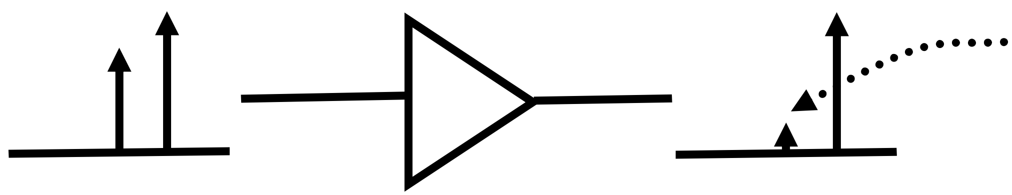
Blocking / desensitization

Assume as input signal:

For a non-linear system the gain will be:

$$x(t) = A_1 \cos(\omega_1 t) + A_2 \cos(\omega_2 t)$$

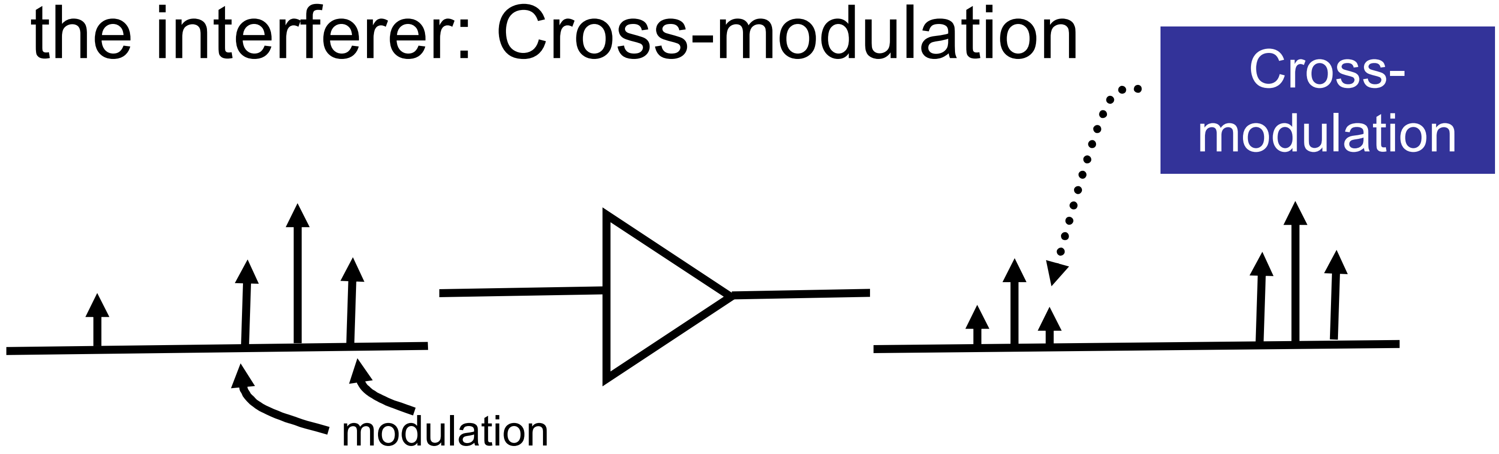
$$y(t) \approx (\alpha_1 + \tfrac{3}{2}\alpha_3 A_2^2) * A_1 \cos(\omega_1 t)$$



For $\alpha_3 < 0$ and a sufficient large interferer A_2 the wanted signal $A_1 * \cos(\omega_1 t)$ can be blocked because the gain reduces to zero.

Cross-modulation

When a small desired signal and a strong modulated interferer passes through a nonlinear system, the small signal gain of the weak desired signal is modulated by the modulation of the interferer: Cross-modulation



SENSITIVITY

Sensitivity

The minimum (power) signal level (in dBm) that a system can detect with an acceptable SNR is called the sensitivity of that system:

$$P_{sensitivity} = P_{Rsource} + 10\log(F) + SNR_{\min,\,out} + 10\log(B)$$

With:

$P_{Rsource}$: the noise of the source resistance: -174 dBm/Hz (kT) assuming an input power match.

$SNR_{min,out}$: the minimum SNR at the output of the front-end (e.g. at the input of the demodulator),

B: effective system bandwidth over which the noise needs to be integrated.

DECT NF Calculation example

Antenna is 50 Ohm:
available noise power kT

Demod requirement: 16 dB

$$NF_{front-end} = -P_{Rsource} - SNR_{front-end\_out} - 10\log(B) + P_{sensitivity}$$

Smallest BPF =
channel filter:
1.728 MHz

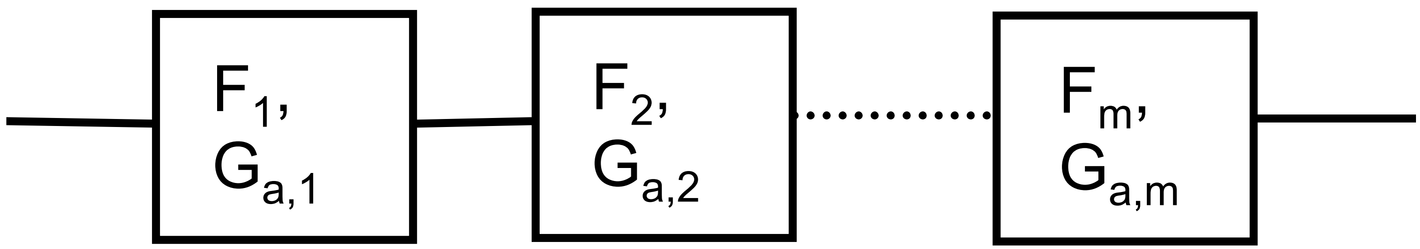
worst case conditions:
-86 dBm (sensitivity requirement)

$$NF_{front-end} = 174 - 16 - 86 - 62 = 10\ dB$$

10Log (B)

CASCADING OF SUB-SYSTEMS & SFDR

Friis' formula



System with cascaded sub-systems with noise factor F_m and available gain $G_{a,m}$

$$F_{total} = 1 + (F_1 - 1) + \frac{F_2 - 1}{G_{a,1}} + \ldots + \frac{F_m - 1}{G_{a,1} G_{a,2} \ldots G_{a,(m-1)}}$$

Assumes perfect filtering

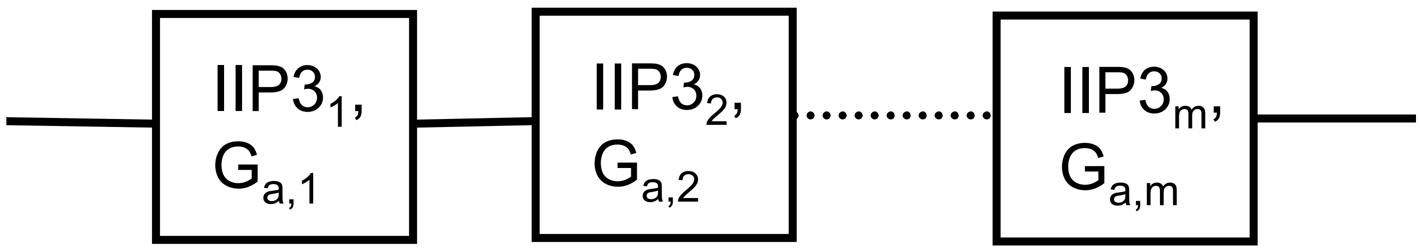
Remarks / implications of Friis' formula

The total noise factor (F_{total}) is referred to the input of the first circuit.

The noise factor F of each sub-system is calculated with respect to the source impedance driving that circuit

The noise factor F of the first stage is dominant when the gain of each stage is reasonable. When the first sub-system has (insertion) loss, then the F of the second sub-system is amplified when referred to the input of the total system.

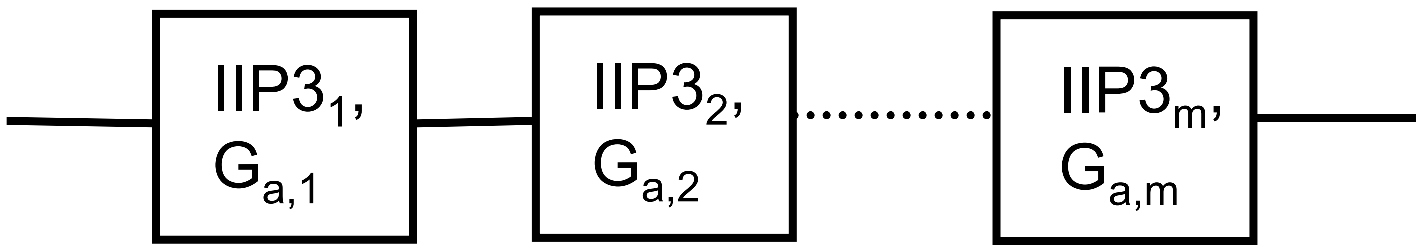
Cascaded IIP3



System with cascaded sub-systems with input IIP3 $IIP3_m$ and available gain $G_{a,m}$

Increasing the gain of a stage results in the decrease of the overall IIP3: the next stage has a larger input signal and will thus produce greater IM3 signals.

Cascaded IIP3 formula



System with cascaded sub-systems with input IIP3 $IIP3_m$ and available gain $G_{a,m}$

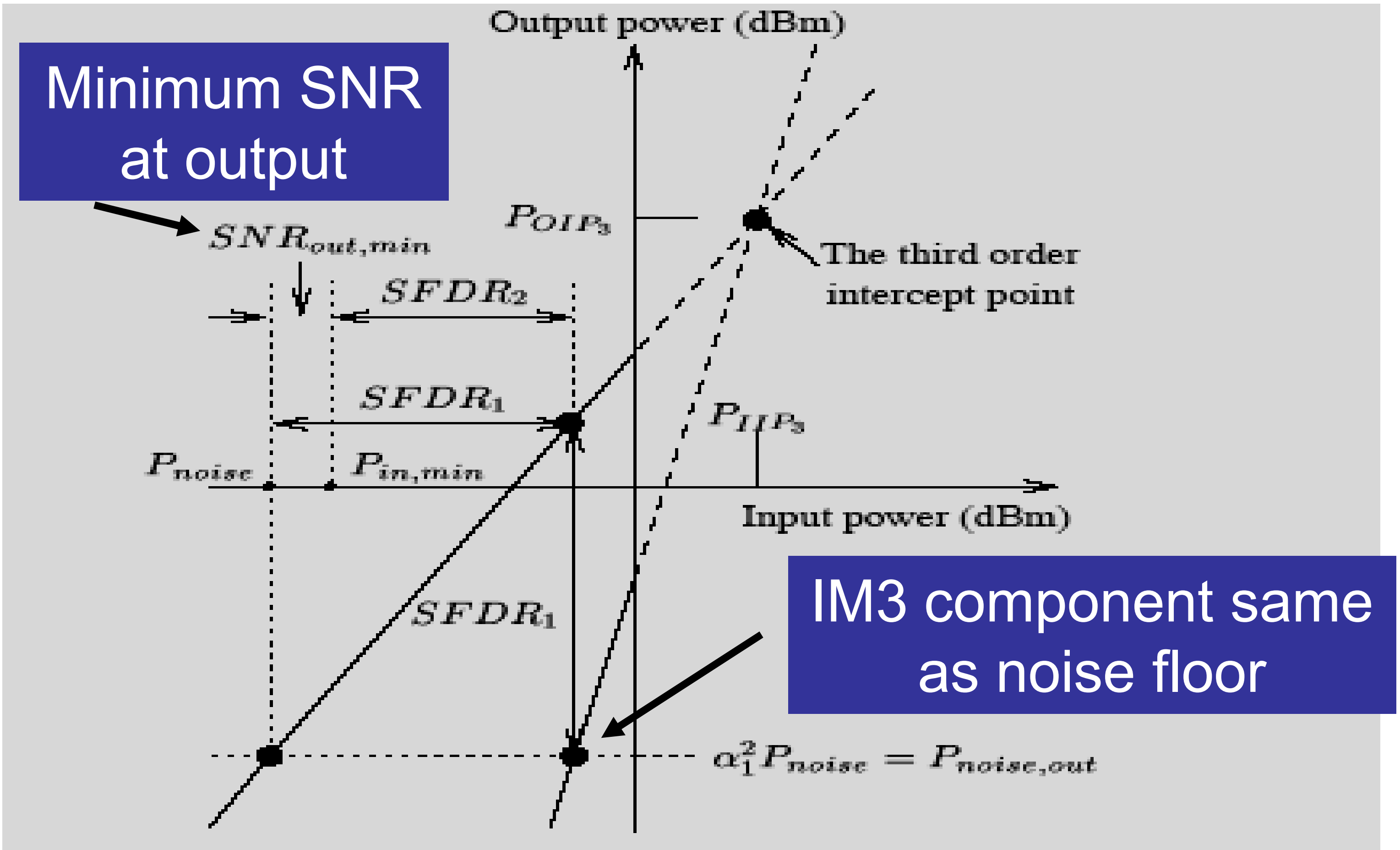
$$\frac{1}{IIP3_{total}} = \frac{1}{IIP3_1} + \frac{G_{a,1}}{IIP3_2} + \ldots + \frac{G_{a,1}G_{a,2}\ldots G_{a,(m-1)}}{IIP3_m}$$

Spurious free dynamic range (SFDR) (I)

We can defined the SFDR as the signal to noise ratio at the output of the system when the power of the third-order inter-modulation products is equal to the noise floor of that system. We can also transfer the SFDR to the input of the system:

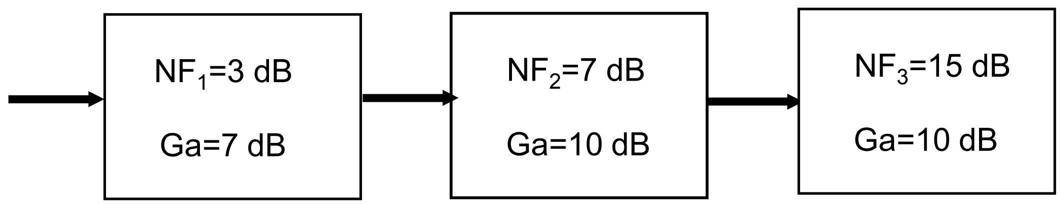
The dynamic range of a system is limited by the noise floor (for weak signals) and by the non-linearity of that system (for strong signals, in-band IM3 components)

Spurious free dynamic range (SFDR) (II)



Calculation example

$$F_{total} = 1 + (F_1 - 1) + \frac{F_2 - 1}{G_{a,1}} + \ldots + \frac{F_m - 1}{G_{a,1} G_{a,2} \ldots G_{a,(m-1)}}$$



First calculation in numerical ratios: F_1=2, Ga_1 =5, etc

$$F_{total} = 2 + \frac{5-1}{5} + \frac{31.6-1}{(5)(10)} = 3.4$$

Which is equal to a noise figure of NF=10Log(3.4)=5.3 dB

Summary WTE lecture 2

- Gain, noise and (non-)linearity of crucial importance for Front-ends.
- Gain definitions quite important: you've got the know the impedance levels normally and the gain definition to interpret a gain figure.
- IIP2 and IIP3 convenient (two tone based) characterization of non-linearity.
- Non-Linearity is the cause of limited SFDR (IM3, IM2 components), densitization/ blocking and cross-modulation.
- Equations for cascaded IIP3 and noise figure usefull to track noise and spurious levels through a system chain: example spreadsheet is on teletops. On chip it is more convenient to use here voltage gain the calculation as matching is normally undesired (3 dB signal loss).

Corresponding course book pages

Read and study:

- **Chapter 1:**
  Section 1.1

- **Chapter 2:**
  Section 2.1
  Section 2.3

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