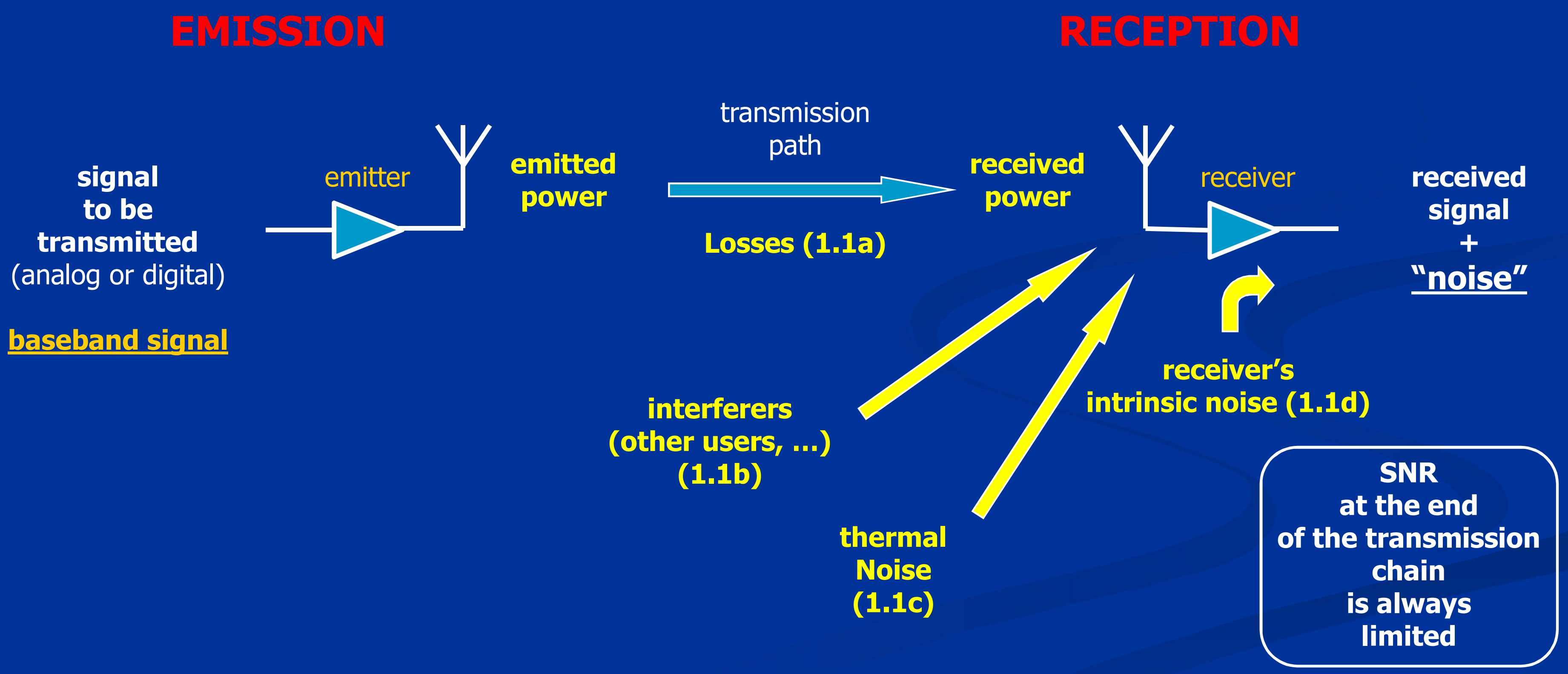
Wireless technologies and applications

RF systems issues

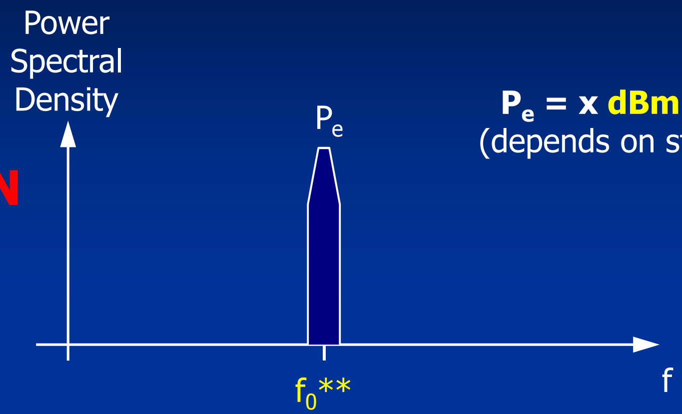
1 - Noise rejection (Signal to Noise Ratio)

- ## 1.1 - Issues



in the frequency domain:

TRANSMISSION



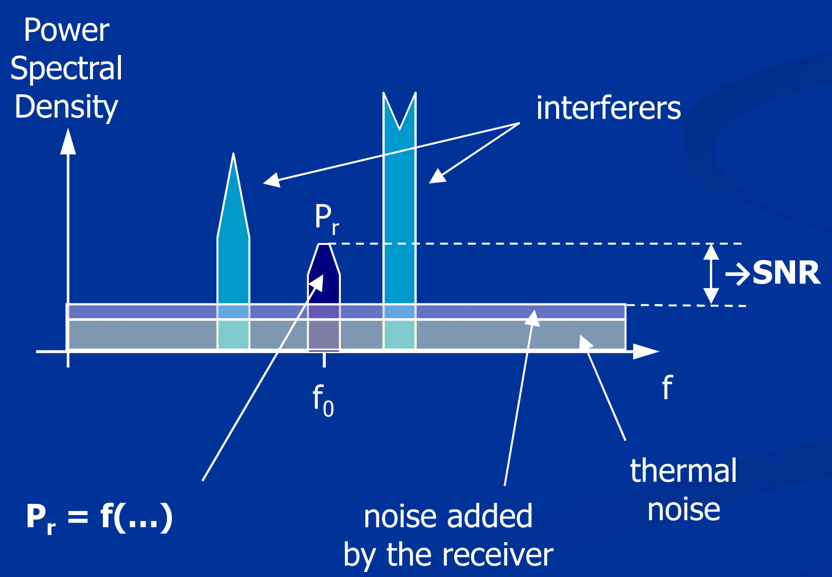
P_e = x dBm* max
(depends on standard)

ex:
GSM → 33 dBm max
DCS-1800 → 30 dBm max
Bluetooth → 0 / 4 / 20 dBm

*** Reminder:**
P (dBm) = 10 log (P / 1mW)

**** notice:**
f_0 ↗ ⇒ channel BW (data rate) ↗
antenna size ↘

RECEPTION



SNR must be sufficient
to guarantee the quality***
of the transmission

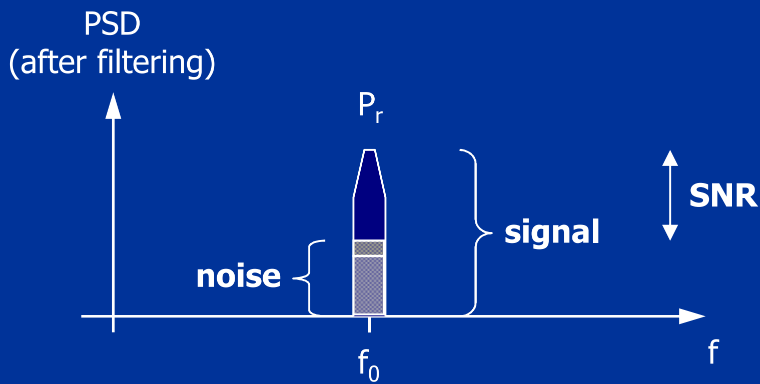
***** Bit Error Rate (BER)**
for digital communications

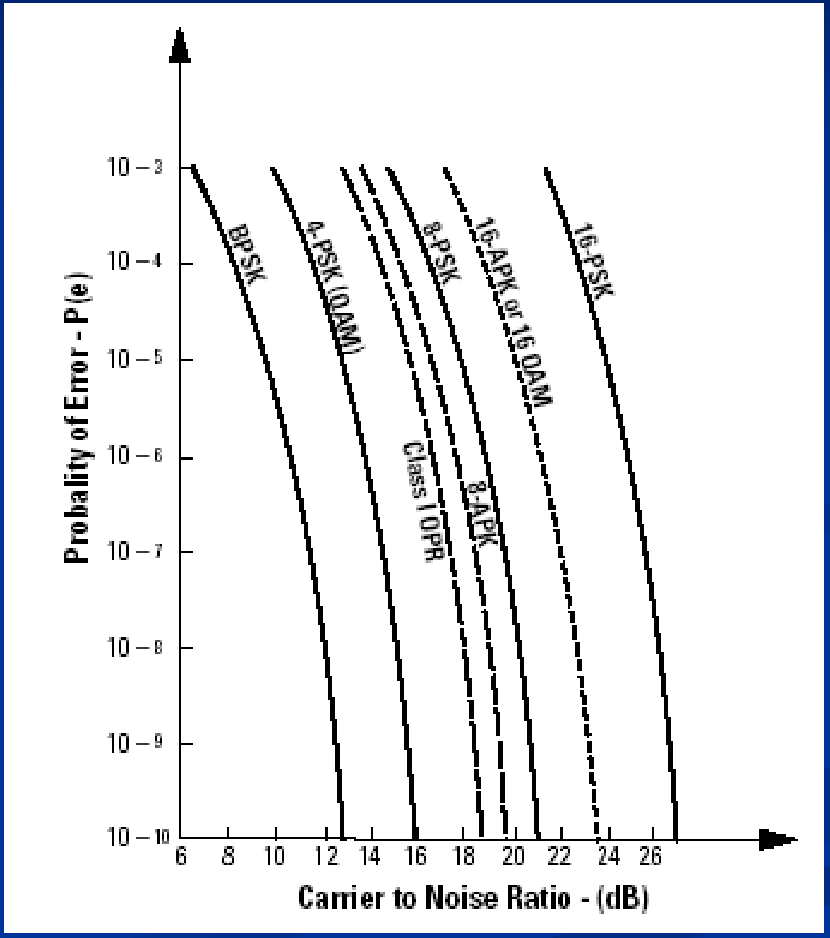
In the receiver, a minimum Signal to Noise Ratio must be guaranteed to maintain the Bit Error Rate at a sufficiently low level.

(BER is never = 0 !)

According to modulation scheme and noise level, a minimum signal level must be received for correct data transmission.

This defines the receiver's sensitivity.





1.1.a – transmission path losses: what net power at the receiving antenna?

Losses depend on the distance d between Tx and Rx and on the carrier wavelength λ:

$$P_{loss} = 10\, log(4\pi\ \ d/\lambda)^2 \qquad \text{(dB)}$$

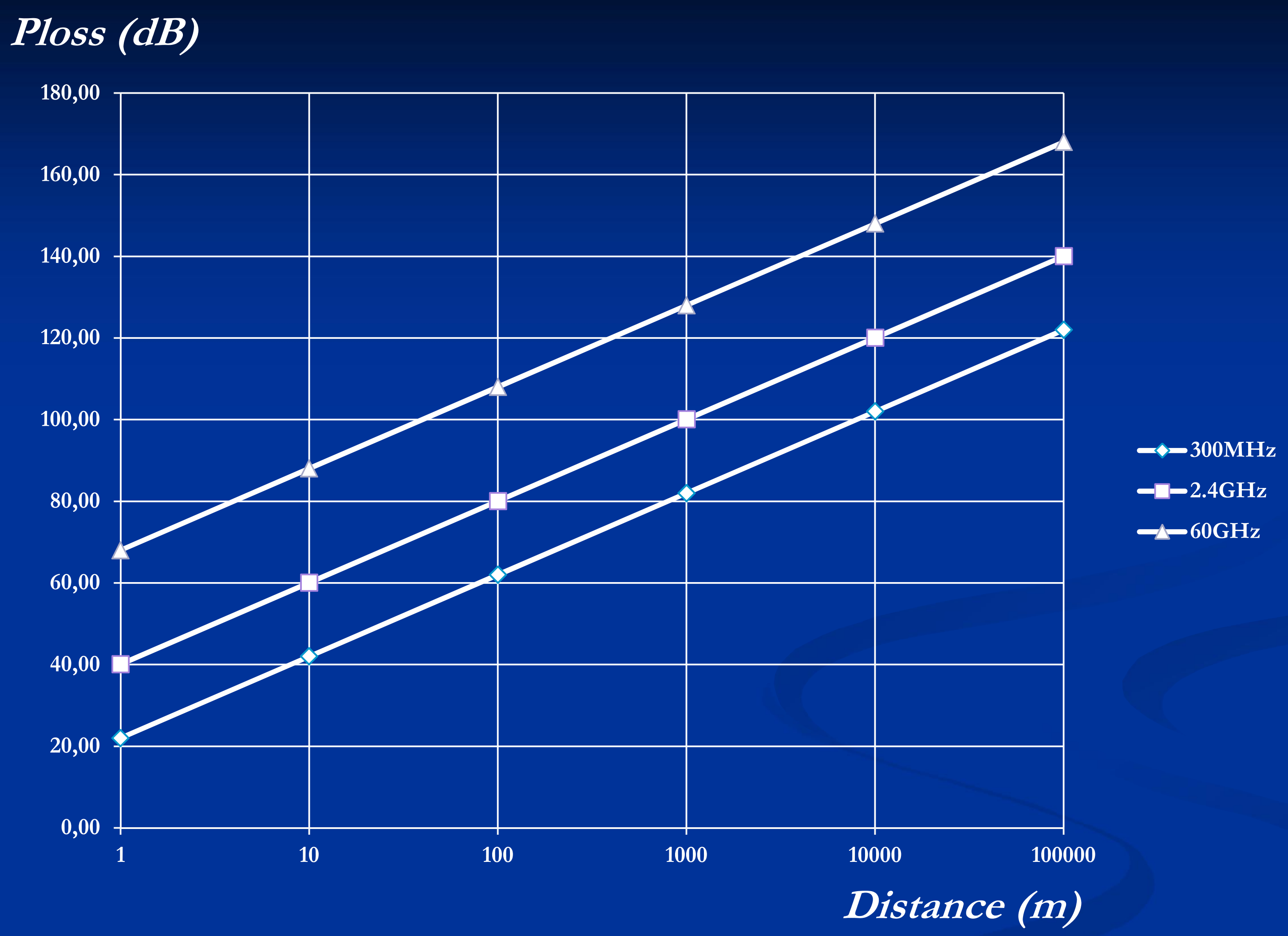
$$\lambda = \frac{300}{f_{carrier}} \qquad (m, MHz)$$

Using practical units: $P_{loss}\,(dB) = 32.45 + 20\log f_{carrier}\ (MHz) + \ 20\log d\ (km)$

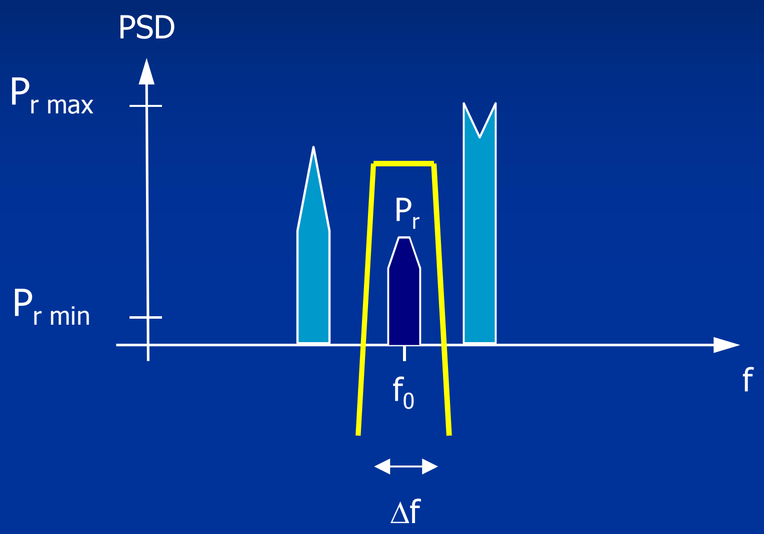
The net received power at the antenna is:

$$P_{Rx} = \ P_{Tx} + \ G_{ATx} - P_{loss} + G_{ARx}$$

P_{Rx}: received power (dBm)
P_{Tx}: transmitted power (dBm)
G_{ATx}: transmitter antenna gain (dB) ≥0
G_{ARx}: receiver antenna gain (dB) ≥0


Ploss (dB)
180,00
160,00
140,00
120,00
100,00
80,00
60,00
40,00
20,00
0,00
1
10
100
1000
10000
100000
300MHz
2.4GHz
60GHz
Distance (m)

1.1.b - interferers or adjacent channels: rejection is achieved in the receiver by channel filtering



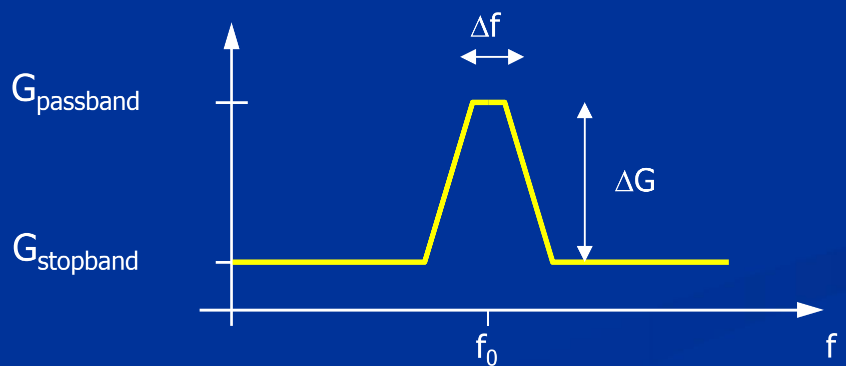
GSM characteristics:

$P_{r\ min} \approx -110$ dBm
$P_{r\ max} \approx -20$ dBm

$\Rightarrow 10^9$ ratio (!!!)

$\Delta f = 200$ kHz

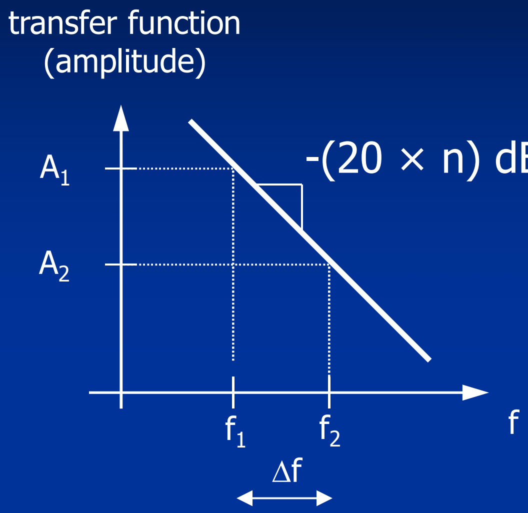
equivalent filtering function of receiver



Δf depends on:
spacing between the channels

ΔG depends on:
- useful channel's power (worst case)
- adjacent channel's power (worst case)
- required SNR

estimation of the required order for the equivalent filter



$-(20 \times n)$ dB/décade (n is the filter order)

$$(A_2/A_1)_{dB} = -20 \times n \log (f_2/f_1)$$

example: 60 dB attenuation required with $\Delta f = 45$ kHz

for $f_1 = 5$ kHz, $f_2 = 50$ kHz $\Rightarrow$ $n = 3$

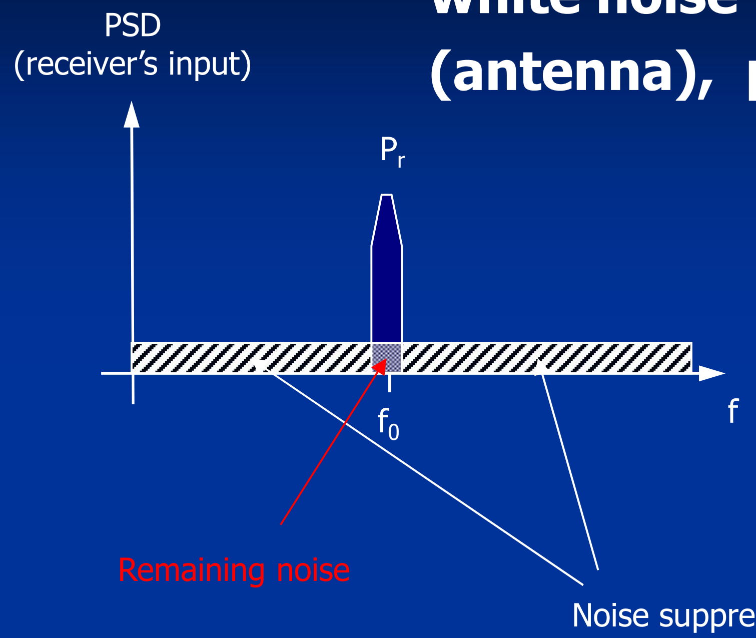
for $f_1 = 900$ MHz, $f_2 = 900{,}045$ MHz $\Rightarrow$ $n \approx 150\,000$

In addition, center frequency f_0 must be tunable, according to the channel of interest $\Rightarrow$ not compatible with a high quality factor passive filter)

$\Rightarrow$ **channel filtering can't be done directly at radio frequency (RF)**

1.1.c – thermal noise:

white noise present at the input of the receiver (antenna), partially filtered by the receiver



$\Rightarrow$ **<u>low bandwidth receivers are more sensitive</u>** (more noise is rejected)

For example, if signal source is an antenna, aimed at sky with effective temperature $T_{antenna}$=30ºK, then the received power spectral density is:

$PSD_{received} = k\ T_{antenna} = -174 + 10 \log(30/290) = -183.8$ dBm/Hz

The term: -174(dBm/Hz) is the thermal level for 290K; the term: +10 log(30/290) corrects for a system noise temperature of 30 K. The noise power at the antenna is the PSD multiplied by the receiver's bandwidth B.

1.1.d – receiver's noise:

induced by the different elements of the receiver

$\Rightarrow$ the lower the better !

Issues to investigate:

How much added noise for a given element in the chain?

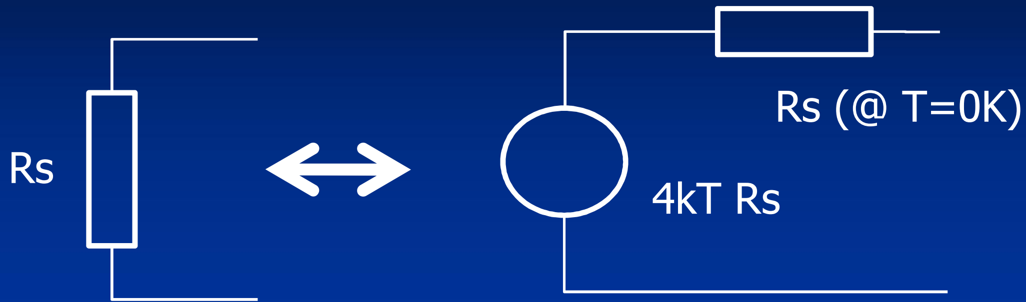
How much added noise for the whole chain?

References:

[1] Richard J. Mohr, Mohr on Receiver Noise: Characterization, Insights & Surprises
[2] Friis, H.T., Noise Figures of Radio Receivers, Proc. Of the IRE,July, 1944, pp 419-422

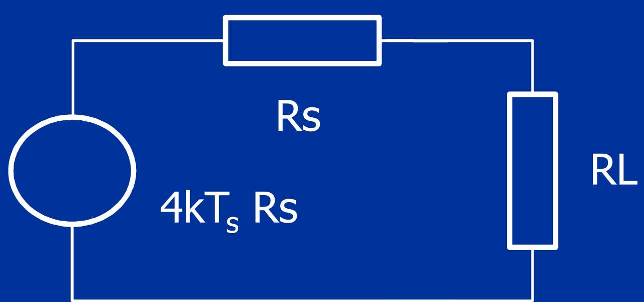
How much added noise for a given element in the chain?

The input noise can be modeled as a noisy resistor Rs :



When this noise source is connected to a load:

$$P_{RL} = \underbrace{\underbrace{\underbrace{\underbrace{4kTs\ \ Rs}_{V^2/Hz}\left(\frac{RL}{Rs+RL}\right)^2}_{V^2/Hz}\frac{1}{RL}}_{W/Hz}\ B}_{W}$$



When the source is conjugate matched to the load (Rs = RL*):

$$P_{RL} = k\ Ts\ \ B$$

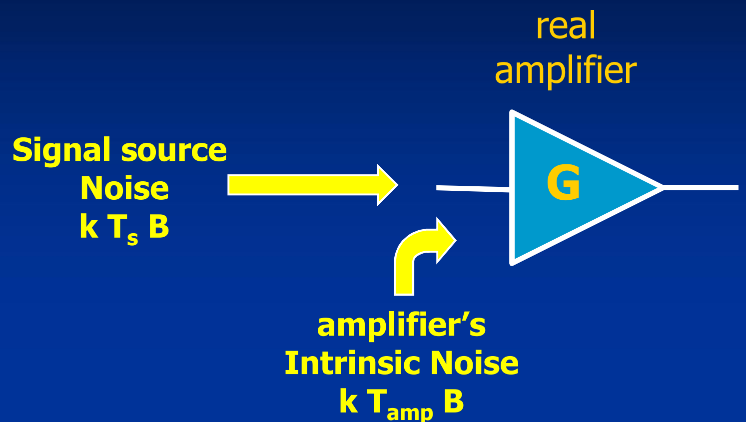
kT = -174 dBm / Hz
(4 10^{-21} W/Hz)
at 290 °K

B = bandwidth of the receiver
≈ channel bandwidth

•True whatever the resistor value
as far as source is matched to the load

•T_s is the noise temperature of the source

Similarly, the noise added by an element of the chain, let's say an amplifier with power gain G, can be modeled by its equivalent noise temperature T_{amp} :



$N_{out} = G\, N_{in}$

Total input noise (signal source and amplifier):

$$N_{intotal} = \frac{N_{out}}{G} = k\,(T_s + T_{amp})B = k\,T_s\,B\left(1 + \frac{T_{amp}}{T_s}\right) = k\,T_s\,B\,F$$

Where: $F = \left(1 + \frac{T_{amp}}{T_s}\right)$ Is the noise factor of the amplifier

F is defined by IEEE standard when $T_s = T_0 = 290K$

Noise figure NF is also used, it is simply NF = 10 log(F), expressed in dB

What lies behind noise factor F?

For a noiseless amplifier, T_{amp} = 0 Kelvin and therefore F = 1

A real, noisy amplifier exhibits a non-zero noise temperature and then F increases.

The noise factor is a measure of the amplifier's added noise in terms of $k\,T_s\,B$ with $T_s = T_0 = 290K$. More precisely, $F - 1$ measures how many $k\,T_0\,B$ are added by the amplifier to the noise coming from the signal source.

For example, if NF = 6dB, F = 4. This means that the amplifier adds <u>$3\,k\,T_0\,B$</u> to the noise coming from the signal source.

An alternate definition of the noise factor is:

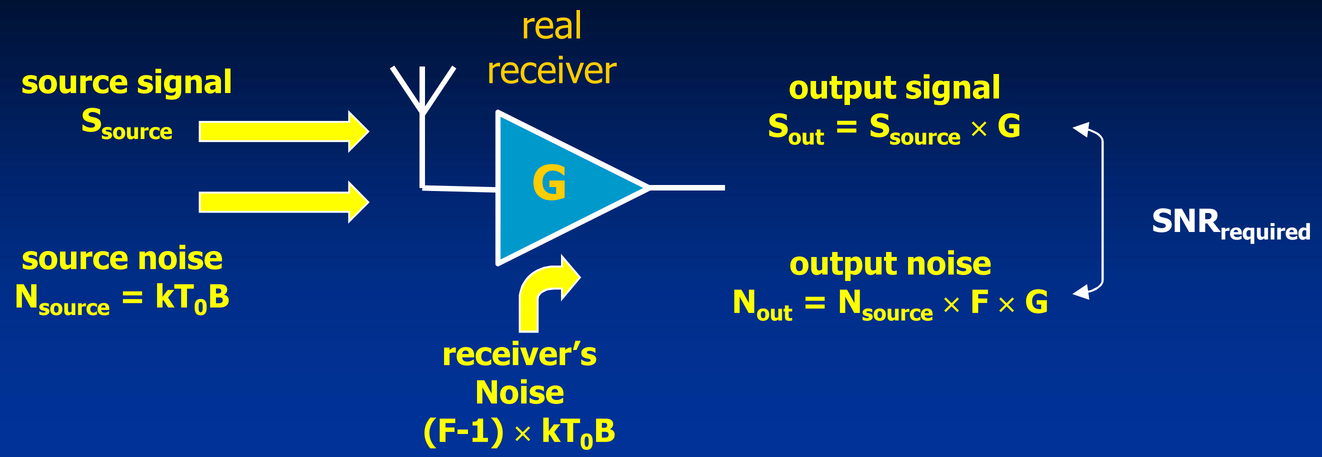
$$F = SNR_{source} / SNR_{out} = (S_{source}/N_{source}) / (S_{out}/N_{out})$$

$$F = \frac{S_{source}/N_{source}}{S_{out}/N_{out}} = \frac{S_{source}}{S_{out}} \times \frac{N_{out}}{N_{source}} = \frac{1}{G} \times \frac{N_{out}}{N_{source}}$$

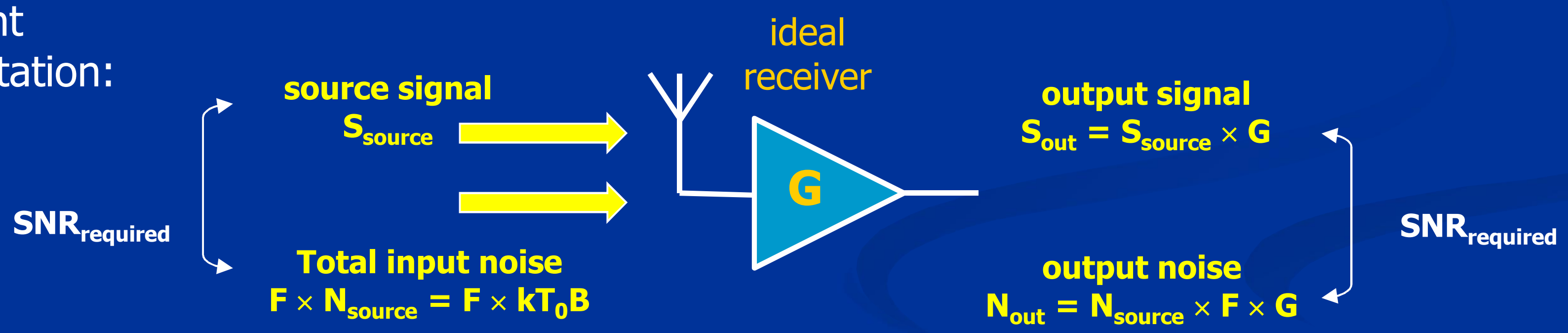
Where N_{source} is the noise <u>only due</u> to the signal source (kT_0 B) with T_0 = 290K

$\Rightarrow N_{out} = F \times G \times N_{source}$ (total noise at the output)

summary:



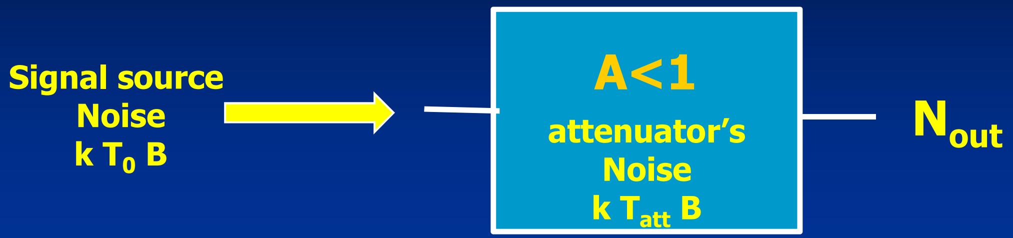
equivalent representation:



<u>input-referred noise</u> (= total noise at the output / gain) <u>:</u> $F \times N_{source} = F \times kT_0B$

in dB: $N_{in\ total} = -174 + 10 \log B + NF$ (dBm)

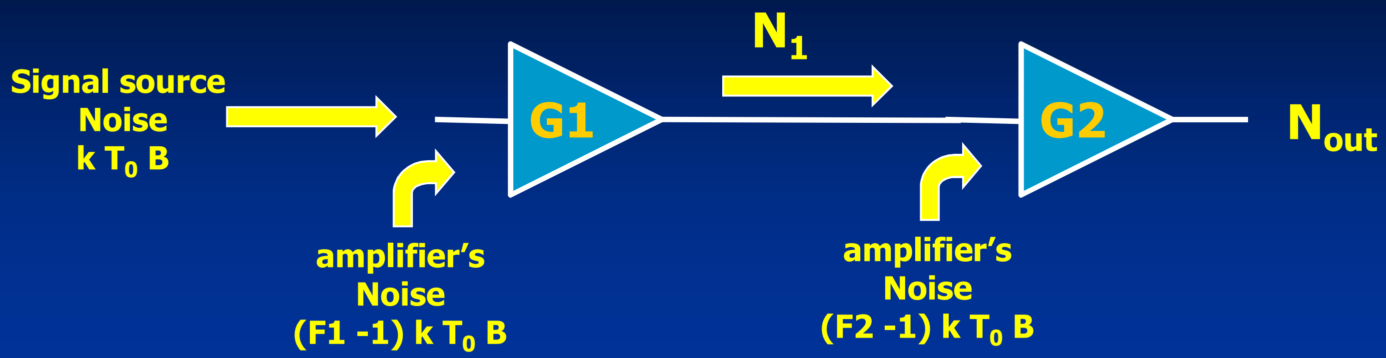
What if we have lossy elements (attenuators)?



$$F = \frac{N_{out}}{A\, N_{source}} = 1 + \frac{T_{att}}{T_0}\,\frac{1-A}{A}$$

Therefore, if $T_{att} = T_0$, the attenuator's noise factor is 1/A. For example, a 3dB attenuator (attenuator's gain is -3dB) exhibits a noise factor F = 3dB

How much added noise for the whole chain?

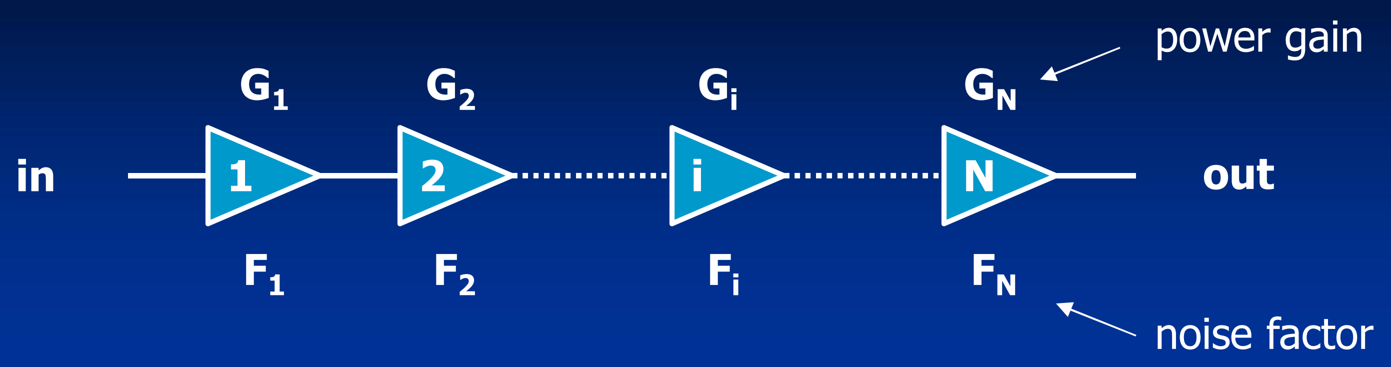


$$N_{out} = [F1\; k\; T_0 B\; G1 + (F2-1) k\; T_0 B] G2$$

$$N_{ineq} = \frac{N_{out}}{G1\; G2} = \left[F1 + \frac{(F2-1)}{G1}\right] k\; T_0 B$$

$$F_{global} = \left[F1 + \frac{(F2-1)}{G1}\right]$$

Noise figure for cascaded elements



If elements are matched:

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

"Friis equation [2]"

⇒ F_i and G_i are <u>NOT</u> in dB

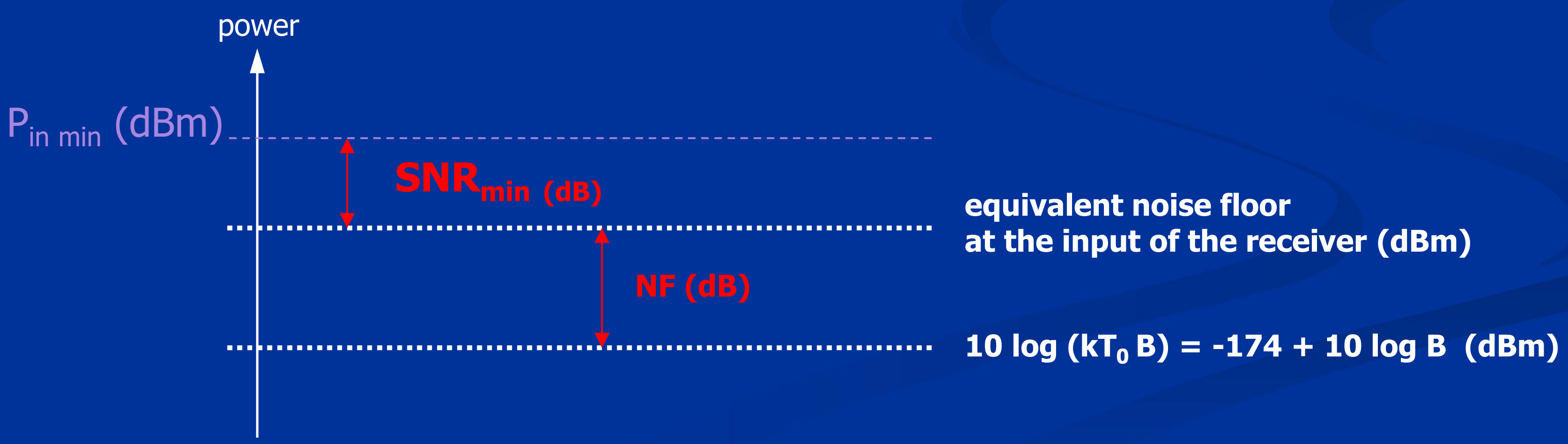
⇒ <u>1^{st} active element in a receiver: Low Noise Amplifier</u>

1.2 - Sensitivity of a receiver

Sensitivity is the minimum power of the input signal which gives a sufficient SNR for correct decoding/demodulation of the transmitted data

$$\text{sensitivity} = P_{in\ min} = kT_0\,B \times F \times SNR_{min}$$

in dB: $$\text{sensitivity (dBm)} = -174 + 10 \log B + NF + SNR_{min\ (dB)}$$



for illustration

MICREL®

MICRF505

850MHz and 950MHz ISM Band Transceiver

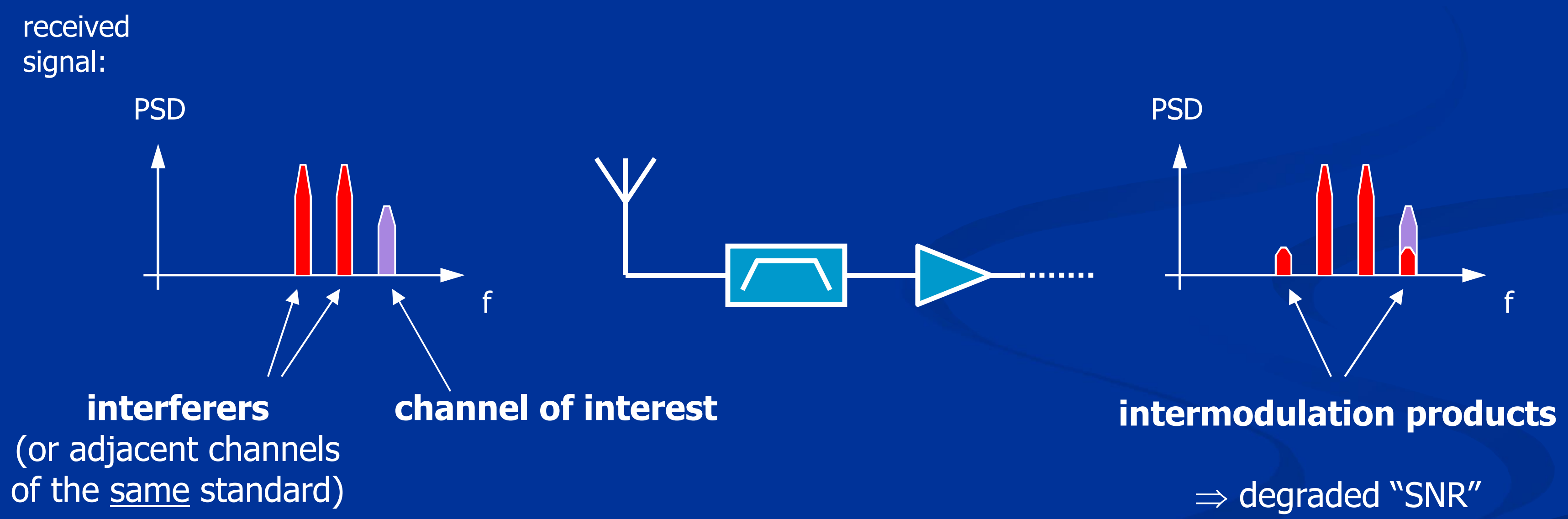
Receive Section						
	Rx Current Consumption	All functions turned on		13.5		mA
		LNA bypass		10.9		mA
		Switch cap filter bypass with LNA		10.9		mA
		Bypass of Switch cap and LNA		8.6		mA
	Rx Current Consumption Variation	Over temperature		4		mA
	Receiver Sensitivity	2.4kbps, β = 16, SC=50kHz, BER 10^{-3}		-111		dBm
		4.8kbps, β = 16, SC=50kHz, BER 10^{-3}		-110		dBm
		19.2kbps, β = 8, SC=200kHz, BER 10^{-3}		-107		dBm
		38.4kbps, β = 4, BER 10^{-3}		-104		dBm
		76.8kbps, β = 2, BER 10^{-3}		-101		dBm
		125kbps, β = 2, BER 10^{-3}		-100		dBm
		200kbps, β = 2, BER 10^{-3}		-97		dBm
	Receiver Maximum Input Power	125kbps, β = 2		-12		dBm
		20kbps, β = 10		-10		dBm
	Receiver Sensitivity Tolerance	Over temperature		4		dB
		Over power supply range		1		dB
	Receiver Bandwidth		50		350	kHz

14 dB
⇒ power ratio = 25
⇒ theoretical distance ratio = 5 !

3 dB
⇒ power ratio = 2
⇒ theoretical distance ratio = 1,4

2 - Linearity

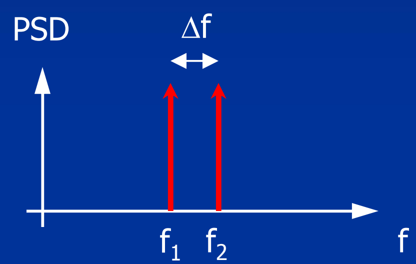
- ## 2.2 - Issues

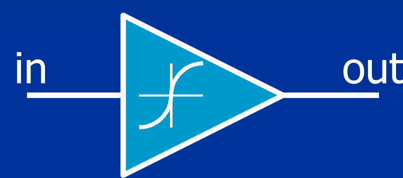


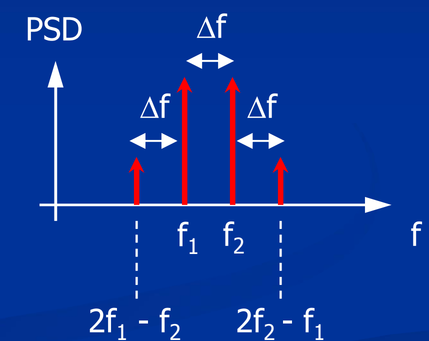
non-linear element:

$in = A \sin(2.\pi.f_1.t) + A \sin(2.\pi.f_2.t)$

$out = a.in + b.in^2 + c.in^3 + \ldots$







fundamental

$a.in \rightarrow f_1, f_2$

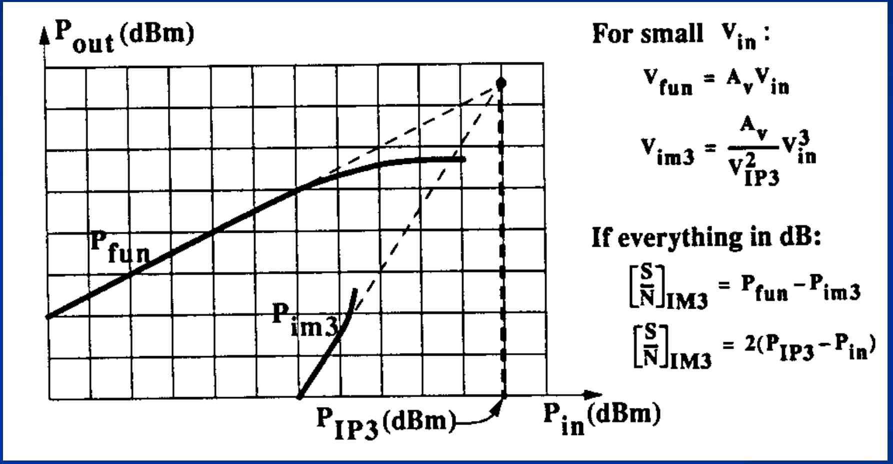
$b.in^2 \rightarrow 2.f_1, 2.f_2, f_1 + f_2, f_1 - f_2$

$c.in^3 \rightarrow 3.f_1, 3.f_2, 2.f_1 + f_2, 2.f_2 + f_1, 2.f_1 - f_2, 2.f_2 - f_1$

Out of band harmonics and intermodulation products suppressed by filtering

In-band intermodulation products

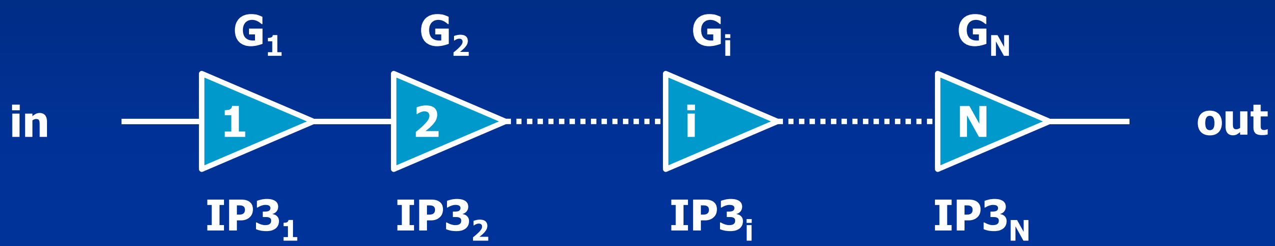
non-linearity is quantified by
"Input-Referred Third-Order Intermodulation Intercept Point" (IP3)



definition: if input power (P_{in}) is equal to IP3 power (P_{IP3}), the power at the output of 3rd order intermodulation products is equal to fundamental output power

notice: *this is a theoretical value, not necessarily achievable in practice*

2.2 - IP3 for cascaded elements



$$\boxed{\frac{1}{IP3_{total}} = \frac{1}{IP3_1} + \frac{G_1}{IP3_2} + \ldots + \frac{G_1.G_2.\ldots.G_{i-1}}{IP3_i}}$$

⇒ $IP3_i$ and G_i are **NOT** in dB

⇒ **with respect to linearity, the last element in the chain is predominant**

example of characteristics (1/2) :

12. Electrical Characteristics: General (Continued)

This device is manufactured with an industrial (not automotive) grade process and process controls. Although this device may meet certain automotive grade criteria in performance, Atmel can not recommend that this device be used in any automotive application.

All parameters refer to GND and are valid for T_{amb} = 25°C, $V_{VS1} = V_{VS2}$ = 3.0V (1-battery application), V_{VS2} = 6.0V (2-battery application) and $V_{VS2} = V_{VAUX}$ = 5.0V (Base-station Application). Typical values are given at f_{RF} = 433.92 MHz unless otherwise specified. Details about current consumption, timing and digital pin properties can be found in the specific sections of the "Electrical Characteristics".

No.	Parameters	Test Conditions	Pin(1)	Symbol	Min.	Typ.	Max.	Unit	Type*
2.6	Maximum frequency offset in FSK mode	Maximum frequency difference of f_{RF} between receiver and transmitter in FSK mode (f_{RF} is the center frequency of the FSK signal with f_{DEV} = ±16 kHz)	(4)	Δf_{OFFSET}	–58		+58	kHz	B
2.7	Supported FSK frequency deviation	With up to 2 dB loss of sensitivity. Note that the tolerable frequency offset is for f_{DEV} = ±22 kHz, 6 kHz lower than for f_{DEV} = ±16 kHz hence $\Delta f_{OFFSET} \le \pm 52$ kHz	(4)	f_{DEV}	±14	±16	±22	kHz	B
2.8	System noise figure	f_{RF} = 315 MHz	(4)	NF		6.0		dB	B
		f_{RF} = 345 MHz	(4)	NF		6.2		dB	B
		f_{RF} = 433.92 MHz	(4)	NF		7.0		dB	B
		f_{RF} = 868.3 MHz	(4)	NF		9.7		dB	B
		f_{RF} = 915 MHz	(4)	NF		10.3		dB	B
2.9	Intermediate frequency	f_{RF} = 315 MHz		f_{IF}		227		kHz	A
		f_{RF} = 345 MHz		f_{IF}		235		kHz	A
		f_{RF} = 433.92 MHz		f_{IF}		223		kHz	A
		f_{RF} = 868.3 MHz		f_{IF}		226		kHz	A
		f_{RF} = 915 MHz		f_{IF}		238		kHz	A

noise figure

UHF ASK/FSK Transceiver

ATA5423
ATA5425
ATA5428
ATA5429

example of characteristics (2/2) :

2.12	System outband 3rd-order input intercept point	Δf_{meas1} = 1.8 MHz Δf_{meas2} = 3.6 MHz f_{RF} = 315 MHz	(4)	IIP3		−22		dBm	C
		f_{RF} = 345 MHz	(4)	IIP3		−22		dBm	C
		f_{RF} = 433.92 MHz	(4)	IIP3		−21		dBm	C
		f_{RF} = 868.3 MHz	(4)	IIP3		−17		dBm	C
		f_{RF} = 915 MHz	(4)	IIP3		−16		dBm	C
2.13	System outband input 1 dB compression point	Δf_{meas1} = 1 MHz f_{RF} = 315 MHz	(4)	I1dBCP		−31		dBm	C
		f_{RF} = 345 MHz	(4)	I1dBCP		−31		dBm	C
		f_{RF} = 433.92 MHz	(4)	I1dBCP		−30		dBm	C
		f_{RF} = 868.3 MHz	(4)	I1dBCP		−27		dBm	C
		f_{RF} = 915 MHz	(4)	I1dBCP		−26		dBm	C
2.14	LNA input impedance	f_{RF} = 315 MHz	4	Z_{in_LNA}		(44 − j233)		Ω	C
		f_{RF} = 345 MHz	4	Z_{in_LNA}		(40 − j211)		Ω	C
		f_{RF} = 433.92 MHz	4	Z_{in_LNA}		(32 − j169)		Ω	C
		f_{RF} = 868.3 MHz	4	Z_{in_LNA}		(21 − j78)		Ω	C
		f_{RF} = 915 MHz	4	Z_{in_LNA}		(18 − j70)		Ω	C

IP3

input impedance (useful for antenna matching)