Telecom Paris

Transceiver Specifications

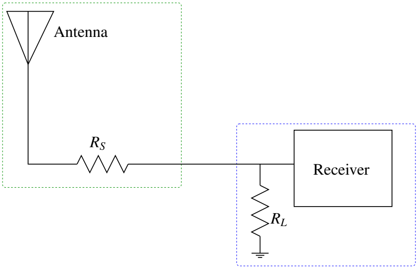
Chadi Jabbour

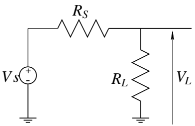
TELECOM 201

Pillars of RF system

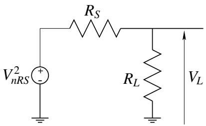
- Power transfer
- Noise
- Non linearity

1-Power transfer





Equivalent circuit
for the input signal



Equivalent circuit
for the R_s thermal noise

$$PSD_{nRs} = V^2_{nRS \ in \ 1 \ Hz} = 4KTR_s$$

Reminders (or not)?

Signal Power in a resistor

$$P_{lin} = \frac{V^2}{R}$$

Power in dBm

$$P_{dBm} = 10 \cdot log_{10}(\text{Power in mW})$$

Relation between Power and Power Spectral Density (PSD)

$$P_{lin} = \int_{Bw} PSD_{lin} \cdot df$$

In case, the signal or noise distribution is uniform in the band

$$P_{lin} = PSD_{lin} \cdot Bw$$

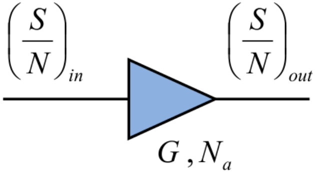
In dBm

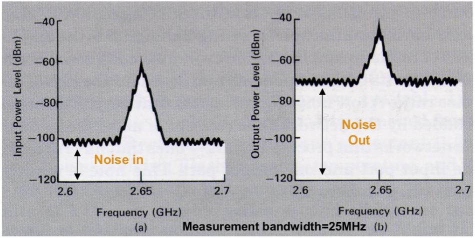
$$P_{dbm} = PSD_{dBm/Hz} + 10 \cdot log_{10}(Bw)$$

1-How to optimise power transfer?

1. Calculate the power at the receiver input P_{in}.
2. Let $\alpha = \frac{R_L}{R_S}$, determine α that allows to maximize P_{in} for a given R_s
3. Set α to the value obtained in the previous question, determine the thermal noise PSD at the receiver input.
4. Calculate the noise PSD in dBm/Hz for a temperature of 17 ^{o}C. (Blotzmann constant K=1.38e-23 J/K)
5. Chadi claims that he has designed a magnificent receiver: The SNR in a 10 MHz band at his receiver output is 20 dB for an input signal of -90 dBm.
   What do you think about Chadi, are his pants on fire?

2-Noise Figure, what for!!

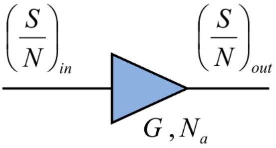


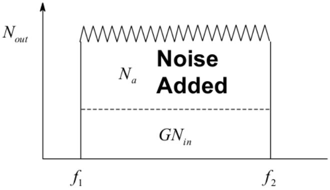


- Noise Figure (NF) is a figure of merit that relates the output Signal to Noise ratio (SNR) to the input SNR of a given block
- If not specified otherwise, NF is defined with respect to the antenna noise
- Most basic definition was defined by Friis in the 1940s

$$F_{lin} = \frac{SNR_{in-lin}}{SNR_{out-lin}} \qquad NF_{dB} = SNR_{in-dB} - SNR_{out-dB}$$

2-Noise Figure, what for!!





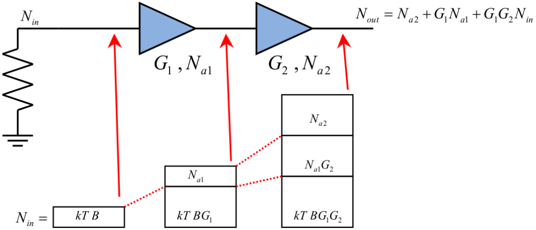
$$Gain = G = \frac{S_{out}}{S_{in}} \qquad N_{out} = N_a + GN_{in}$$

$$F = \frac{\left(\frac{S}{N}\right)_{in}}{\left(\frac{S}{N}\right)_{out}} \Rightarrow$$

$$F = \frac{N_{out}}{GN_{in}} = \frac{N_a + GN_{in}}{GN_{in}} \qquad \textbf{Noise Factor}$$

$$NF\ (\mathrm{dB}) = 10\log\left(\frac{N_a + GN_{in}}{GN_{in}}\right) \qquad \textbf{Noise Figure}$$

Note that G is a power Gain not a voltage gain



$$F_1 = \frac{SNR_{in}}{SNR_1} = \frac{\frac{P_{in}}{N_{in}}}{\frac{G_1 \cdot P_{in}}{G_1 \cdot N_{in} + N_{a1}}} \Longrightarrow N_{a1} = G_1(F_1 - 1)N_{in}$$

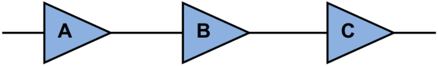
$$F_{12} = \frac{SNR_{in}}{SNR_2} = \frac{\frac{P_{in}}{N_{in}}}{\frac{G_1 \cdot G_2 \cdot P_{in}}{G_1 \cdot G_2 \cdot N_{in} + G_2 \cdot N_{a1} + N_{a2}}} = F_1 + \frac{F_2 - 1}{G_1}$$

Generalization for N stages, Friis formula

$$F_{tot} = F_1 + \frac{F_2 - 1}{G_1} + \ldots + \frac{F_N - 1}{G_1 \cdot G_2 \cdots G_{N-1}}$$

Exercise 2-Noise!!

We have at our disposal 3 amplifiers. We would like to cascade them to obtain a higher gain.



	A	B	C
Gain (dB)	**6.0**	**12.0**	**20.0**
Gain	**4.0**	**16.0**	**100.0**
Noise Figure(dB)	**2.3**	**3.0**	**6.0**
Noise Factor	**1.7**	**2.0**	**4.0**

1. Calculate the noise figure of the chain ABC using Friis equation
2. Compare the calculated result to the one given by the script *AmplifierChain.m*
3. Simulate the configurations BCA and CAB, compare the obtained NFs with ABC.
4. G_a is flexible, it can be set to 0 dB, 6 dB or 12 dB. Try the 3 possibilities and analyze the impact of this change on the NF of the complete chain.

3-Nonlinearity

- Electronic systems have a non-linear behavior due to many reasons:
  - The transistors are not linear
  - Slew Rate
  - Inter symbol interference (ISI)
  - Mismatch

- To model this effect, many models exist:
  - Memory-less models: polynomial,hyperbolic, orthogonal ...
  - Memory aware: Volterra, Hammerstein, Wiener, Narmax...

3-Third order system

Let us consider a third order system:

$$y(t) = \alpha_1 x(t) + \alpha_3 x(t)^3 \qquad \alpha_3 < 0 \text{ in practice}$$

with a two-tone input

$$x = Acos(\omega_1 t) + Acos(\omega_2 t)$$

The system output yields

$$y(t) = \underbrace{(\alpha_1 A + \frac{9}{4}\alpha_3 A^3)\,[cos(\omega_1 t) + cos(\omega_2 t)]}_{\text{Fundamental Terms}} + \underbrace{\frac{1}{4}\alpha_3 A^3\,[cos(3\omega_1 t) + cos(3\omega_2 t)]}_{\text{3rd order harmonics}} +$$
$$\underbrace{\frac{3}{4}\alpha_3 A^3\,[cos((2\omega_1 + \omega_2)t) + cos((\omega_1 + 2\omega_2)t) + cos((2\omega_1 - \omega_2)t) + cos((2\omega_2 - \omega_1)t)]}_{\text{3rd order Inter Modulation Products}}$$

3-Impact of non Linearity

- Gain compression (since $\alpha_3 < 0$).
- Harmonics: New terms arising at 3 times the useful band.
- Inter modulation products: terms arising in the useful RF band

The higher α_3 or/and the higher the input amplitude A, the higher the impact of Nonlinearity

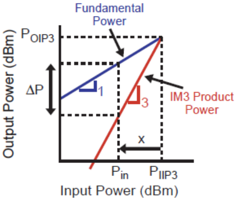
3-Nonlinearity metrics!!

How to characterize non-linearity: 1-dB compression point, Spurious Free Dynamic Range, Second order intercept point IIP2, Third order intercept point IIP3 ...

$$y(t) = \alpha_1 x(t) + \alpha_3 x(t)^3 \text{ with an input } x(t) = Acos(\omega t)$$
$$y(t) = (\alpha_1 A + \frac{3}{4}\alpha_3 A^3)cos(\omega t) + \frac{1}{4}\alpha_3 A^3 cos(3\omega t)$$

The IIP3 is the input amplitude A for which the third harmonic power is equal to the linear power (without compression)

$$\alpha_1 IIP3_{lin} = \frac{1}{4}\alpha_3 IIP3_{lin}^3 \Longrightarrow IIP3_{lin} = 2\sqrt{\frac{\alpha_1}{\alpha_3}}$$



$$IIP3_{dBm} = Pin_{dBm} + \frac{\overbrace{P_{signal-dBm} - P_{harmonic-dBm}}^{IM3 \;\; or \;\; HD3}}{2}$$

IIP3 formula calculation

The linear curve power (blue curve) can be modeled by

$$y_1(x) = x + a$$

The third order curve (red curve) can be modeled by

$$y_3(x) = 3x + b$$

We perform a measurement at an input power P_1, the difference between the two curves is the third inter-modulation term IM3.

$$IM3(P_1) = y_1(P_1) - y_3(P_1) = P_1 + a - 3P_1 - b \Longrightarrow a - b = IM3(P1) + 2P_1$$

The third order intercept point is the point for which the linear term becomes equal to the third order term.

$$y_1(IIP3) = y_3(IIP3) \Longrightarrow IIP3 + a = 3IIP3 + b \Longrightarrow IIP3 = \frac{a-b}{2}$$

We replace $a - b$ by the expression determined earlier.

$$IIP3 = P_1 + \frac{IM3(P_1)}{2}$$

Exercise 3 -Nonlinearity!!

We will use the amplifier A employed in the previous exercise. We will model its non linear behavior using the following equation:

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

1. Use the script *Amplifier_NL.m* to plot the SNDR vs Pin curve. Explain the behavior of the curve
2. Observe two plotted spectrums for the two input powers. Compare the HD3 values and explain the obtained difference.
3. Calculate the IIP3 of the amplifier.

Exercise 3-Nonlinearity (con)!!

The gain of amplifier A is not sufficient to receive very low input signals ($P_{in} < -90 dBm$). We will use the complete chain ABC.

4. Calculate the IIP3 of the full chain using the script *AmplifierChain_NL.m*.

5. Observe carefully the output spectrums of the second and third stages. What can be noticed?

6. G_a is flexible, it can be set to 0 dB, 6 dB or 12 dB. Try the 3 possibilities and analyze the impact of this change on the IIP3 of the complete chain.

References

- https://www.qsl.net/va3iul/Noise/Understanding%20Noise%20Figure.pdf
- https://www.microwaves101.com/encyclopedias/noise-figure
- https://www.electronicdesign.com/what-s-difference-between/what-s-difference-between-third-order-intercept-and-1-db-compression-point
- https://www.microwaves101.com/encyclopedias/compression-point
- https://www.microwaves101.com/calculators/859-cascade-calculator

To go beyond

- Chapter 2 of “RF Microelectronics” of Behzad Razavi. Publisher: PHPTR
- Chapter 4 of “RF System Design of Transceivers for Wireless Communications” of Qizheng Gu. Publisher: Spinger