HPA
(High Power Amplifiers)

Basics of Active and Nonlinear High-Frequency Electronics

Nonlinear electrical modeling of transistors for CAD

ADS

Michel CAMPOVECCHIO

$f > 1\,\text{GHz}$

Université de Limoges
Università degli Studi di Brescia
Aston University
Universidad del País Vasco / Euskal Herriko Unibertsitatea / The University of the Basque Country
Universitatea Tehnică din Cluj-Napoca

Prerequisites :

- Linear analogue circuits
- Resistive and reactive circuits
- Energy and dissipated power
- Transient and steady state conditions.
- Low-pass / high-pass / band-pass filters
- Bode diagram
- Voltage and current sources
- Thevenin / Norton.
- Bipolar and field effect transistors
- Small signal equivalent circuit models
- Input / output impedances.
- Voltage, current and power gains.
- Static and dynamic load lines

Part I : Michel Campovecchio (michel.campovecchio@unilim.fr)

- Lectures : 12 H - Tutorials : 15 H → Lectures and Tutorials 27 H

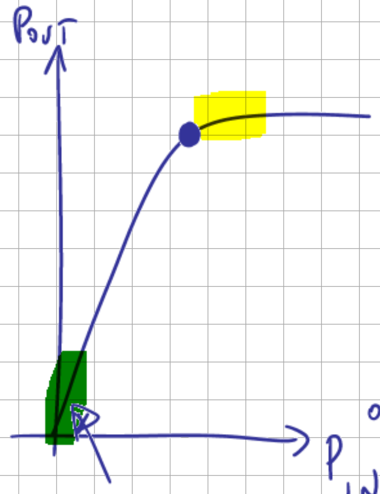
Part II : Jean Michel Nebus (jean-michel.nebus@unilim.fr)

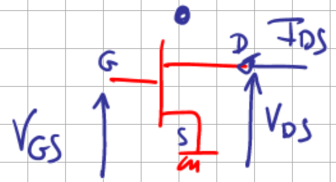
- Lectures : 12 H - Tutorials : 15 H → Lectures and Tutorials 27 H

- Chapter I : Introduction to active high-frequency circuits in communication systems
- Chapter II : Introduction to the Non-linear Electrical Modeling of microwave transistors
- Chapter III : Design method of narrow-band power amplifiers
- Chapter IV : Architectures of high-frequency mixers
- Chapter V : Architectures of $\boxed{\text{wideband}}$ resistive and distributed power amplifiers *(depending on the course progress)*
- Chapter VI : Architectures of non-linear active circuits controlled by cold HEMTs

FET (Field Effect Transistor)

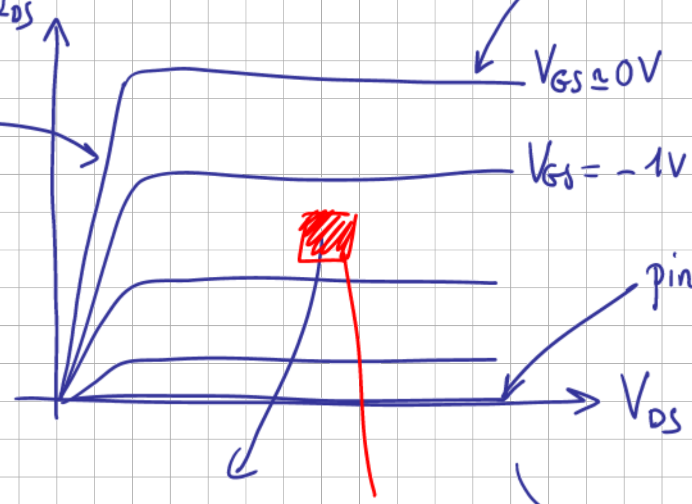
HEMT (High Electron Mobility Transistor)





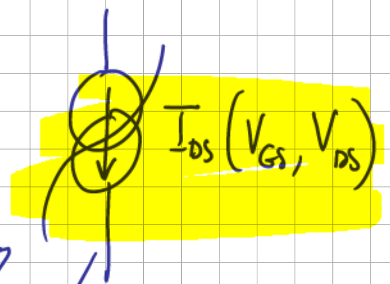
saturated region

ohmic region



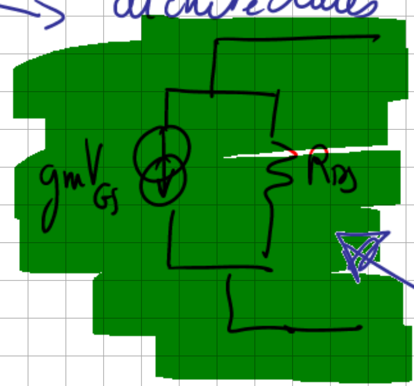
pinch-off voltage V_p

$I_{DS}(t) =$



study analytically simple circuits

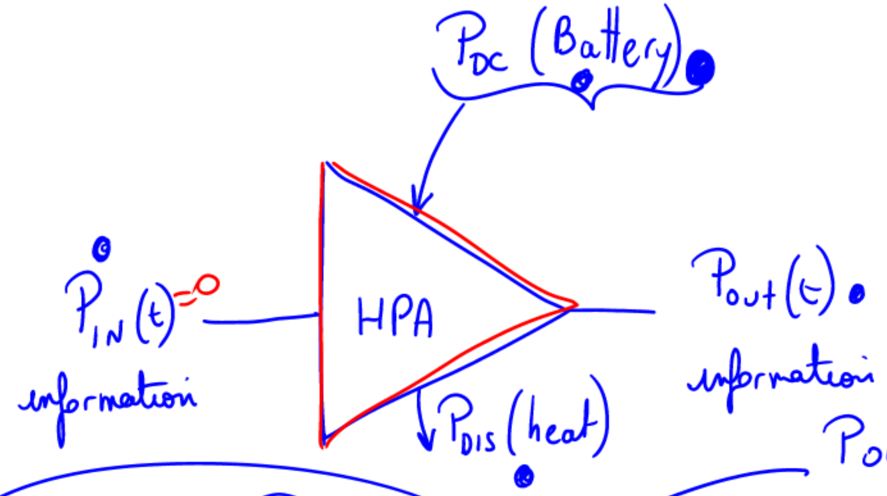
architectures



Bias

Chapter I :

Introduction to active high-frequency circuits in communications systems



$$P_{IN} + P_{DC} = P_{OUT} + P_{DIS}$$

$$P_{DIS} = P_{DC} - (P_{OUT} - P_{IN})$$

$$= P_{DC} - PAE \times P_{DC}$$

$$P_{OUT} - P_{IN} = PAE \times P_{DC}$$

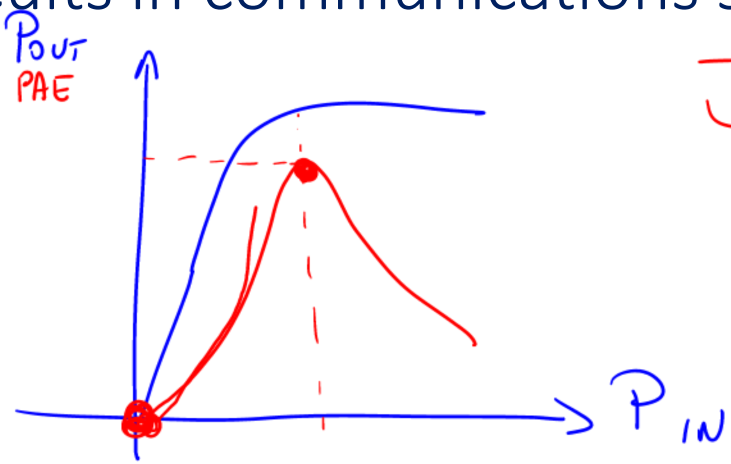
$$P_{DIS} = P_{DC}(1 - PAE)$$

$$PAE = \frac{P_{OUT} - P_{IN}}{P_{DC}}$$

Power Added Efficiency

$$0 < PAE < 1$$

$$T = k \times P_{DIS}$$

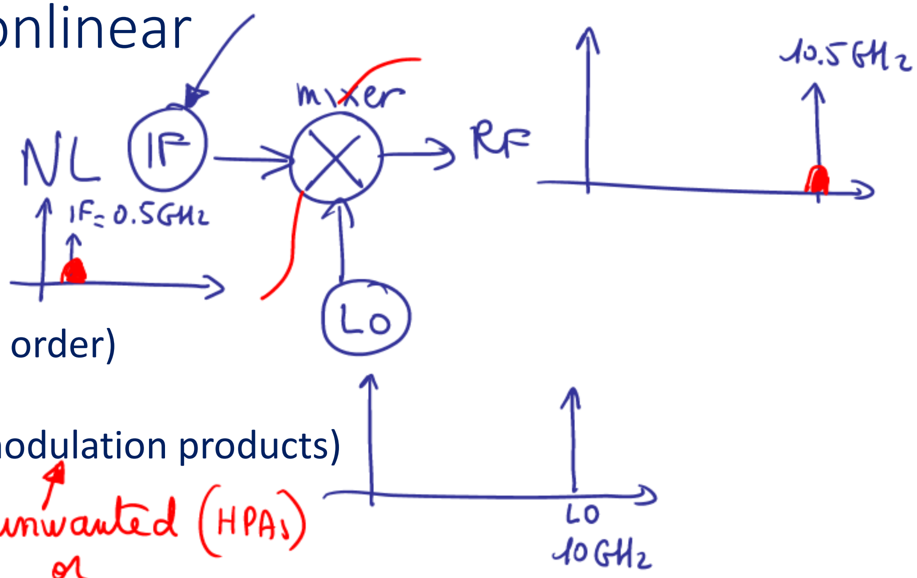


I - Differences Active/Passive & Linear/Nonlinear

1) Power Losses / Gain / Bias

2) Linearity / Non-linearity

3) Frequency generation of nonlinear devices (Nonlinearity order)
   - a) Single carrier (harmonics)
   - b) Multiple carriers (example of two carriers → intermodulation products)

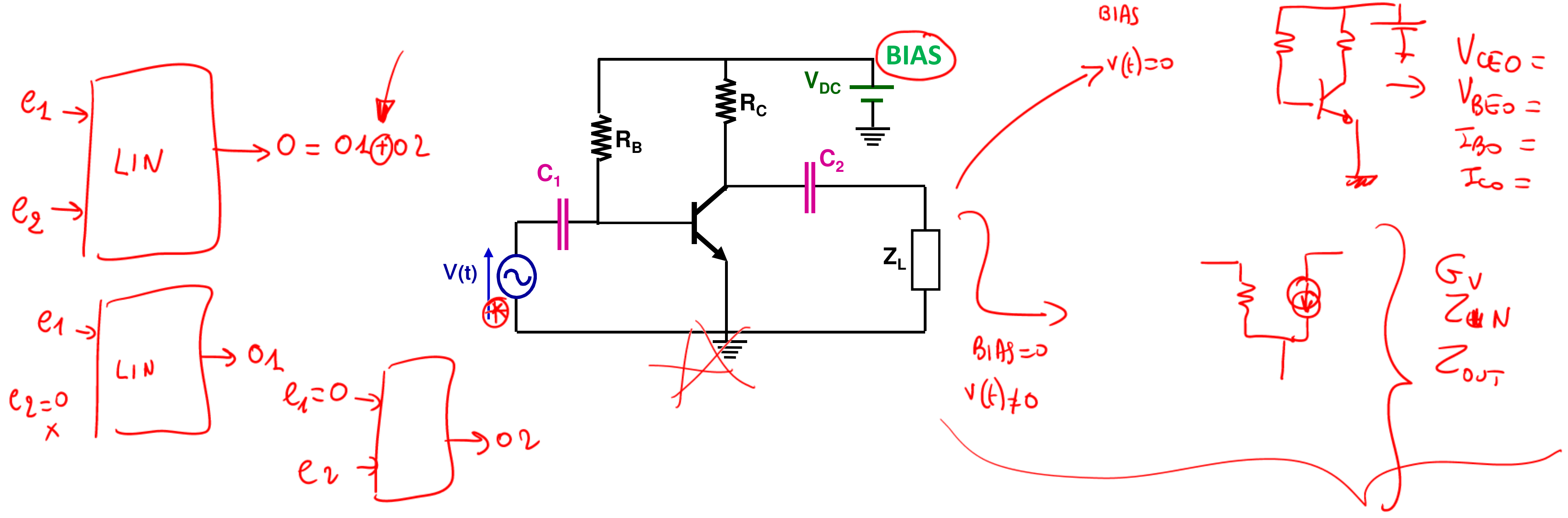


unwanted (HPAs)
or
wanted (mixers)

I - Differences Active/Passive & Linear/Nonlinear

1) Power Losses / Gain / Bias

- A passive circuit cannot give power gain but only losses
- A passive circuit is linear and its response does not depend on the signal amplitude
- On the contrary, a power gain greater than unity is linked to active circuits and bias
- An active circuit can be linear or nonlinear depending on the signal amplitude (diode, FET, …)



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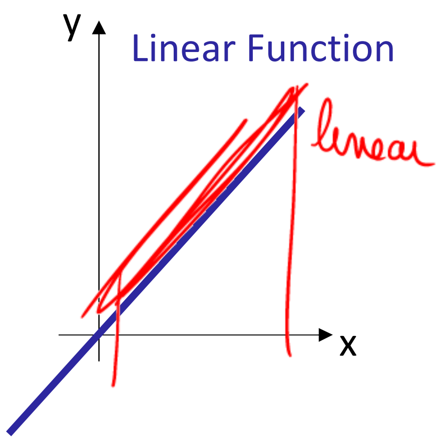

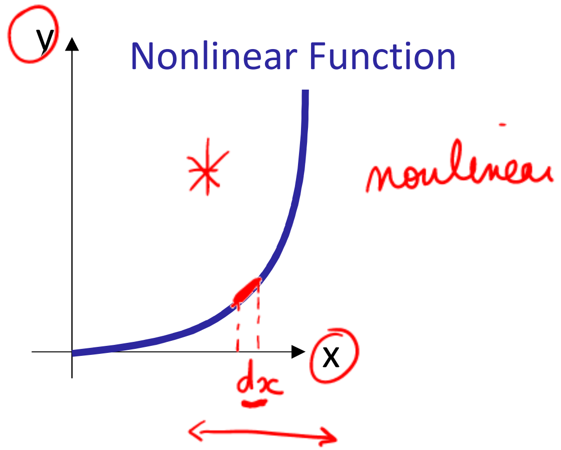

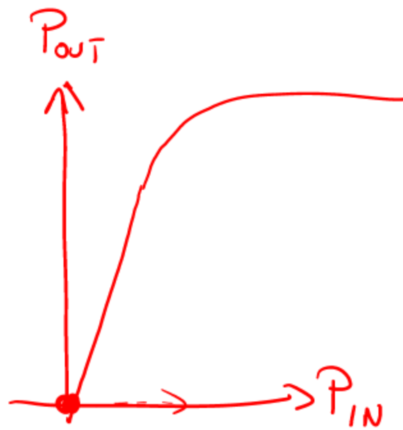

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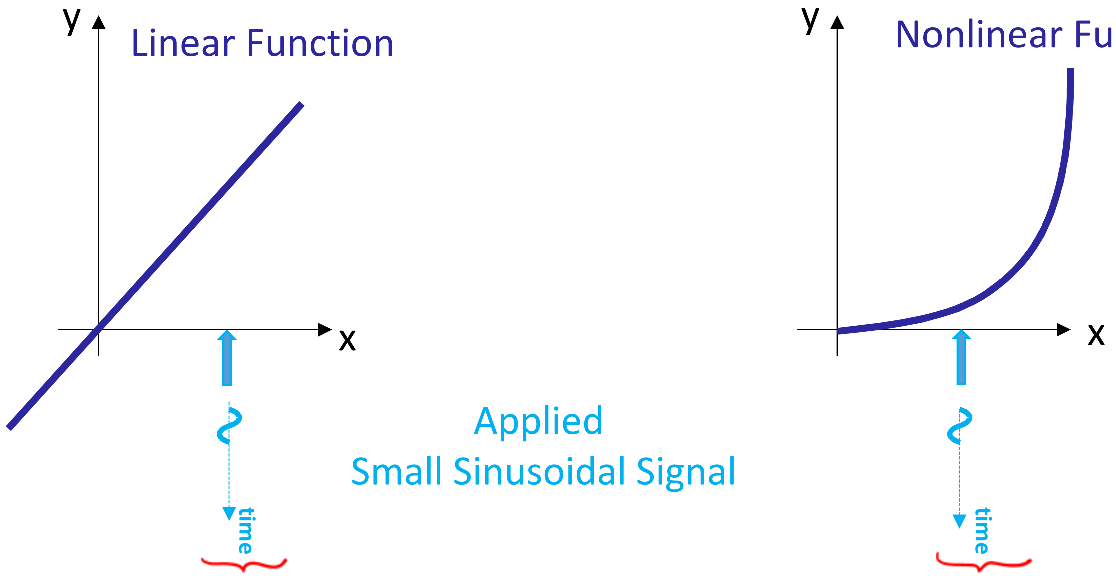

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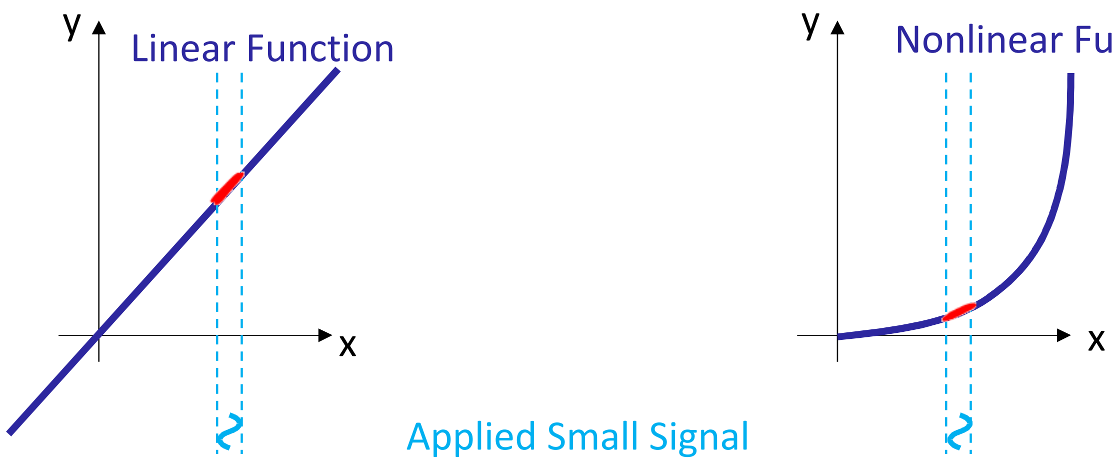

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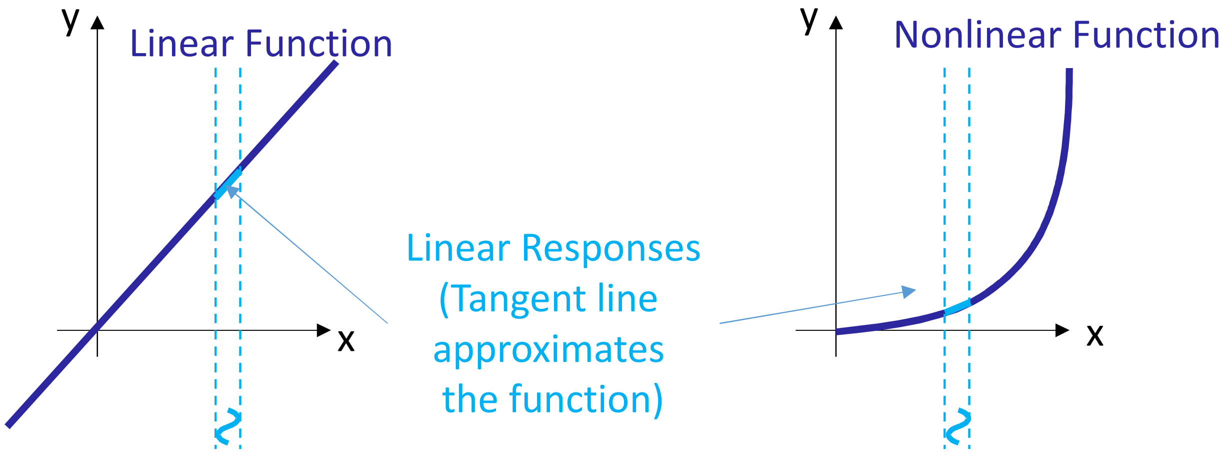

Linear and Nonlinear circuits give a linear response to small signals

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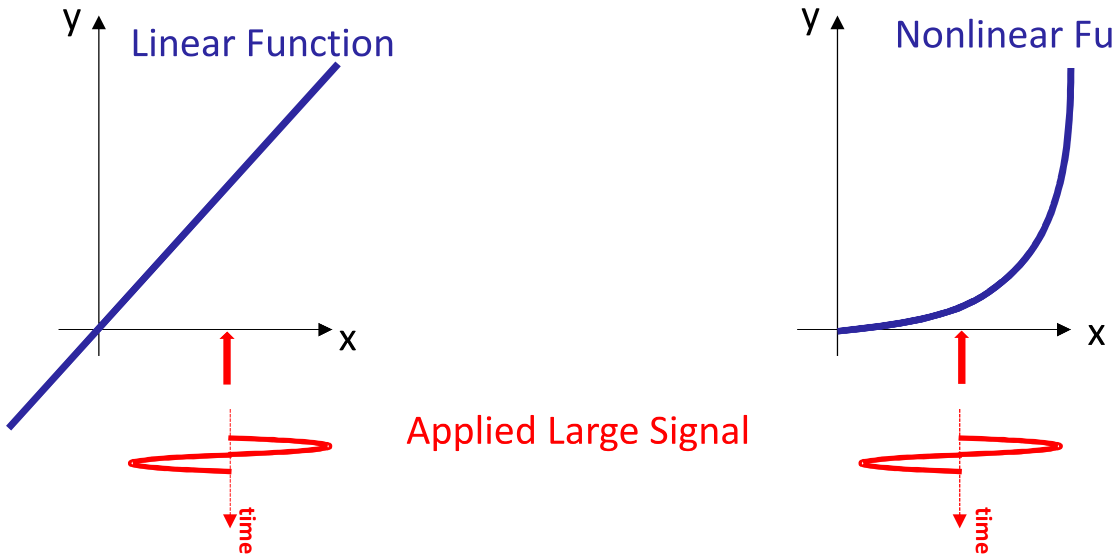

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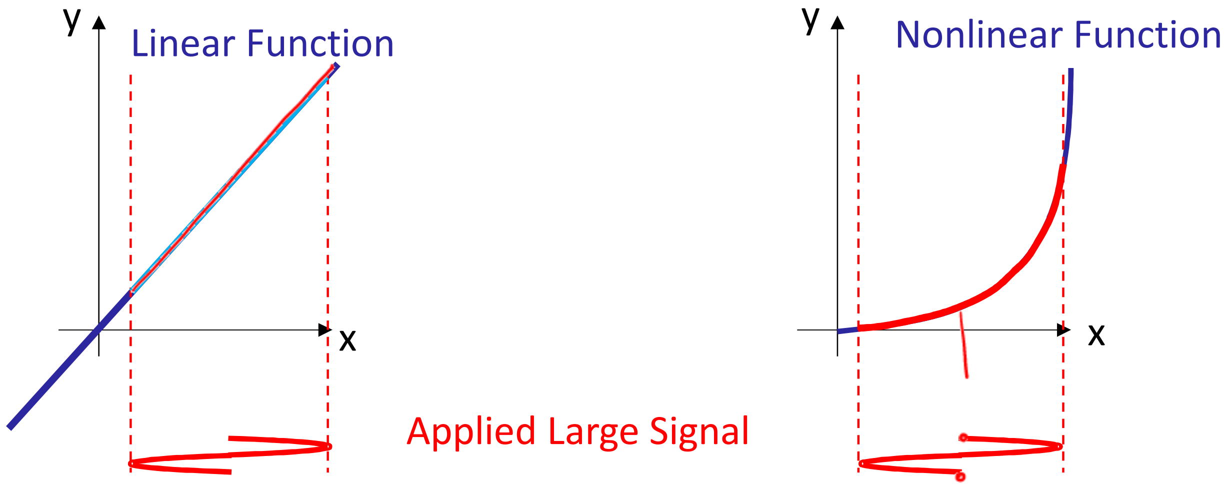

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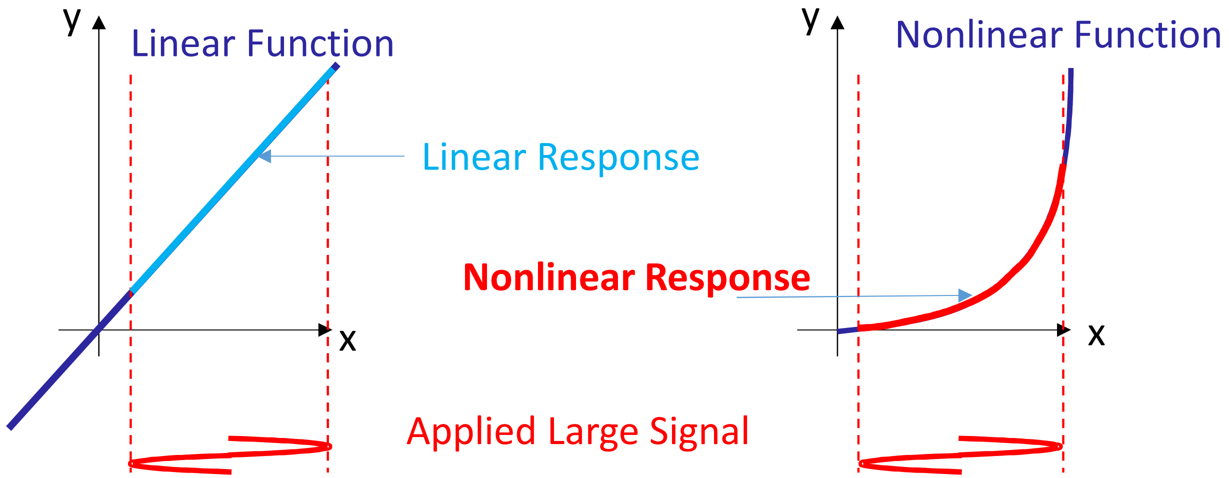


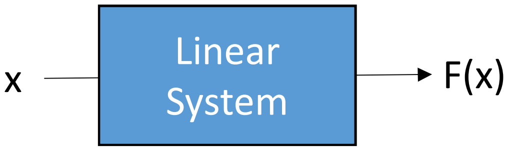
Linear circuits remain linear in the case of large signals

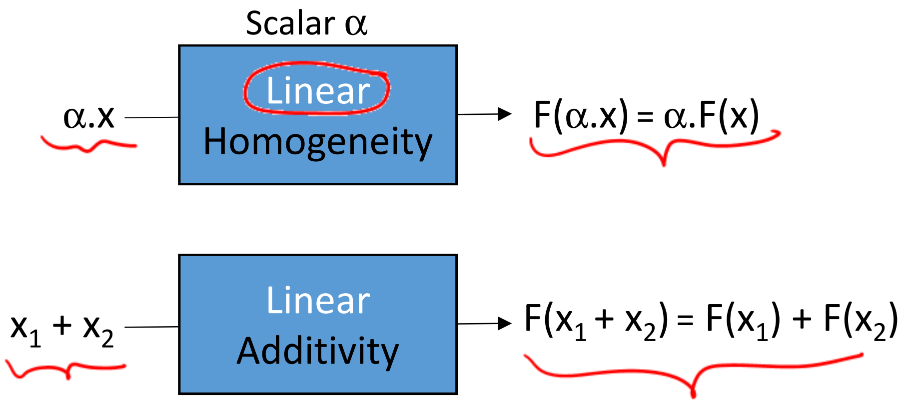
Nonlinear circuits give nonlinear responses to large signals → Harmonic generation in frequency domain

I - Differences Active/Passive & Linear/Nonlinear

2) Linearity (superposition principle)

A system whose response F(x) satisfies the superposition principle is called a **linear system**.
The superposition can be defined by two simple properties : **additivity** and **homogeneity**



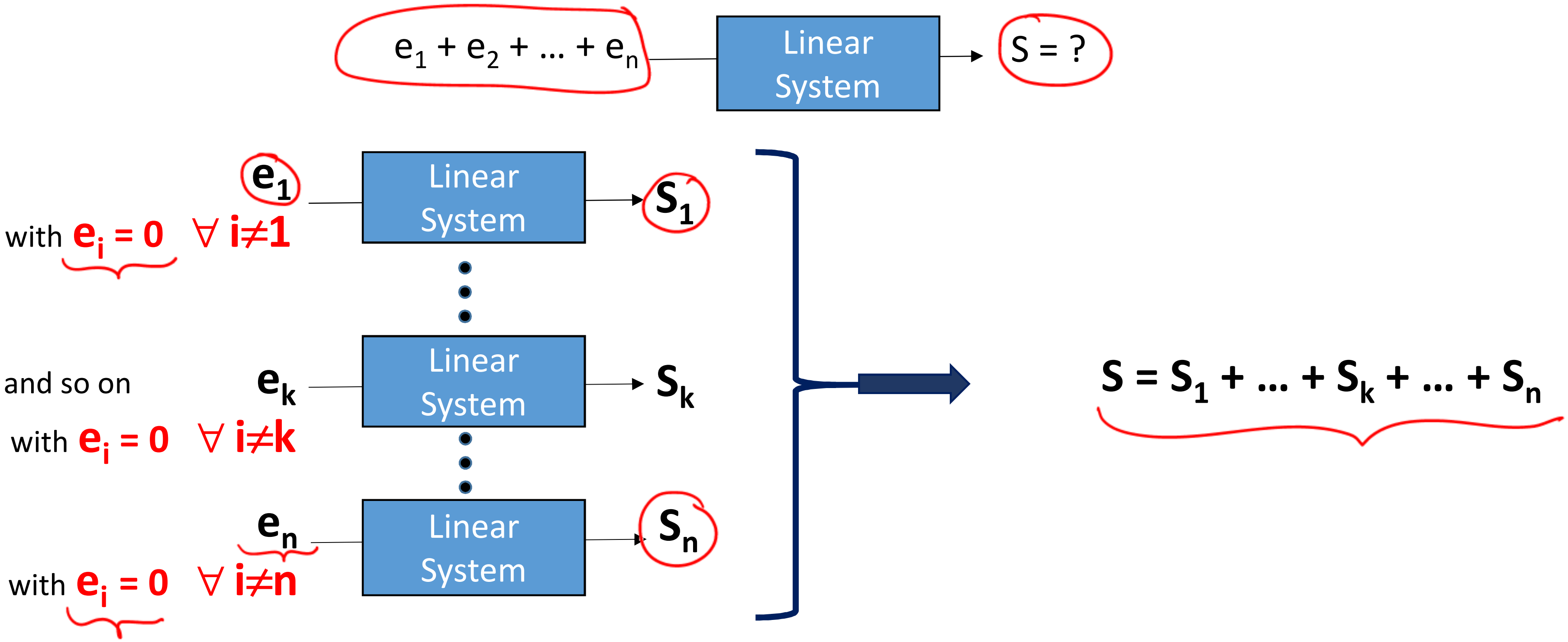


I - Differences Active/Passive & Linear/Nonlinear

2) Linearity (superposition principle)

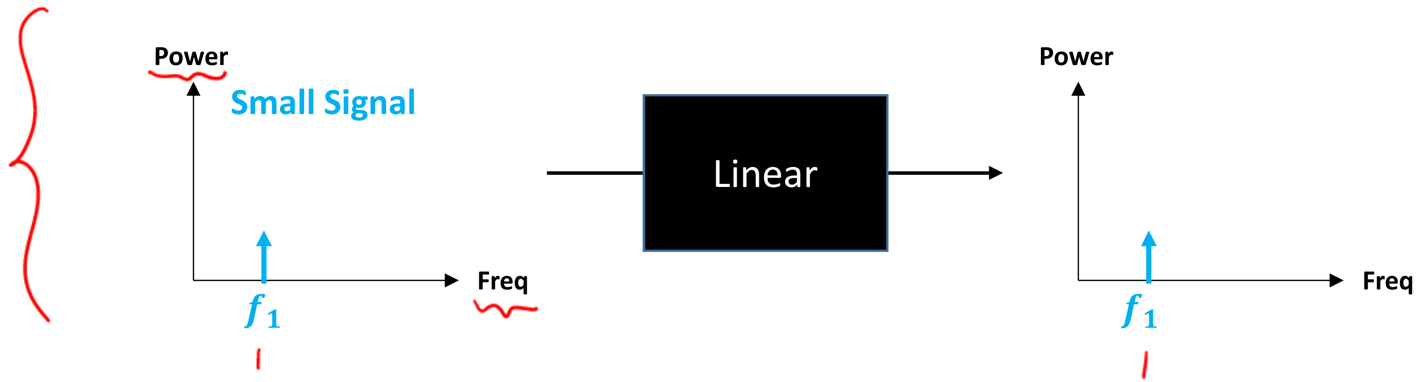
In the case of electrical circuits, the **superposition theorem** states that :

the response of a linear circuit to n independent sources equals the algebraic sum of the n responses caused by each independent source acting alone assuming that all the other independent sources are replaced by their internal impedances.



I - Differences Active/Passive & Linear/Nonlinear

2) Linearity / Non Linearity (single carrier)



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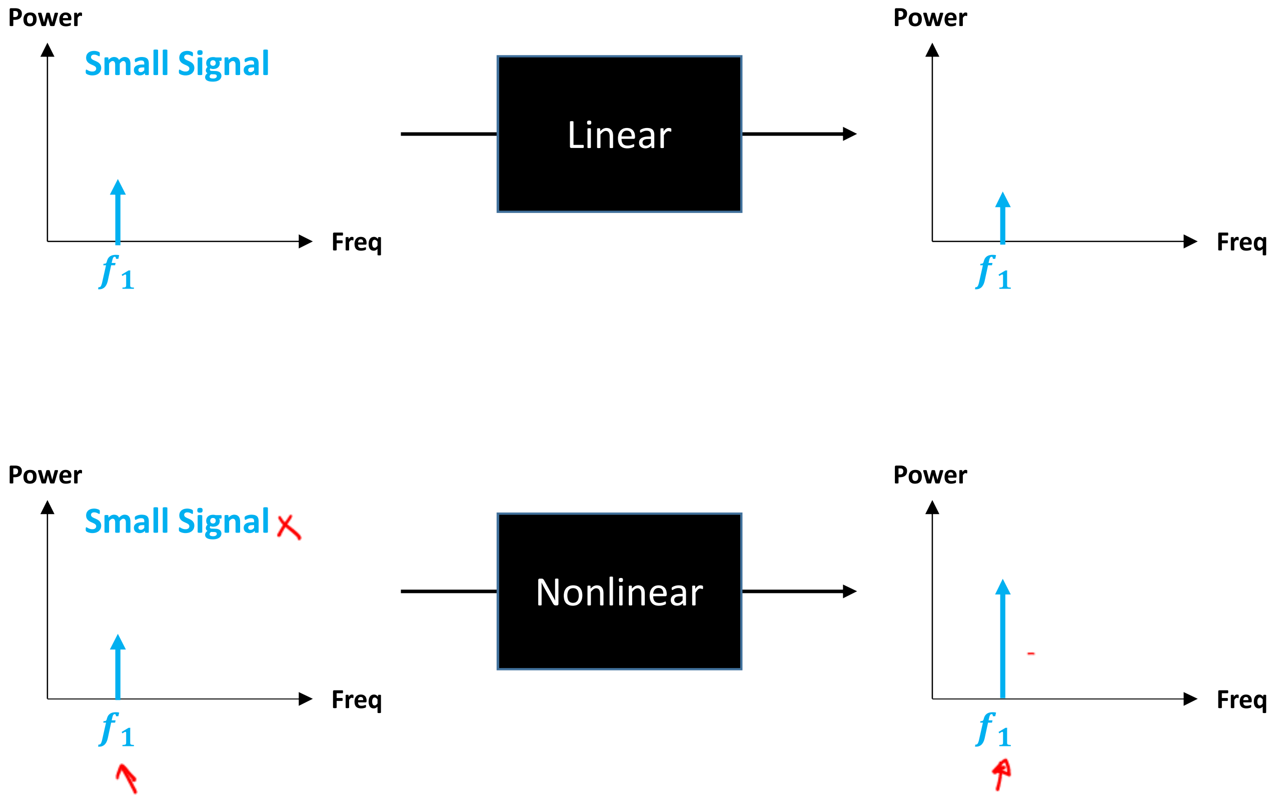
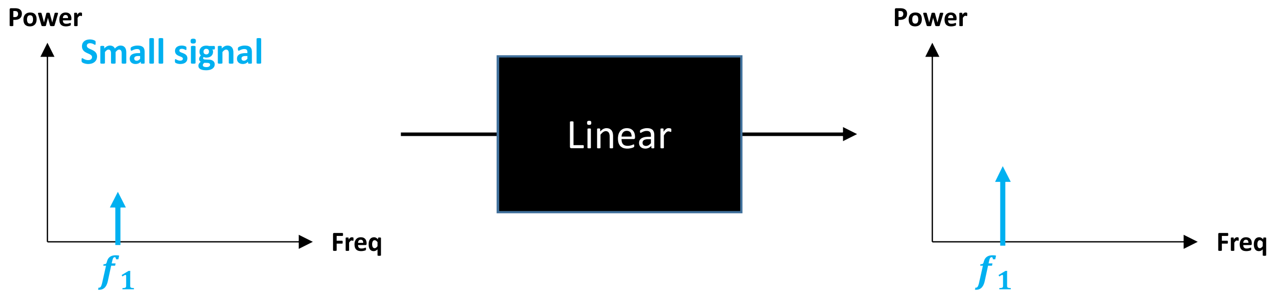


Whatever the type of device (linear or nonlinear), its response to small signals remains linear

I - Differences Active/Passive & Linear/Nonlinear

2) Linearity / Non Linearity (single carrier)



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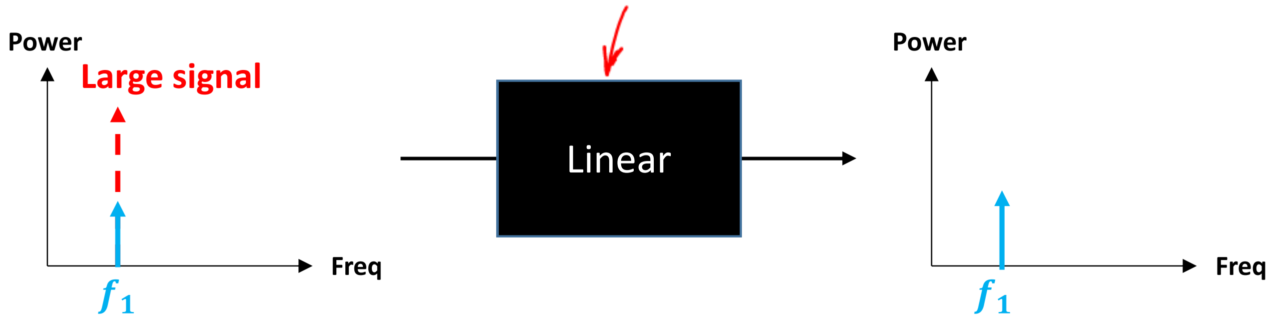

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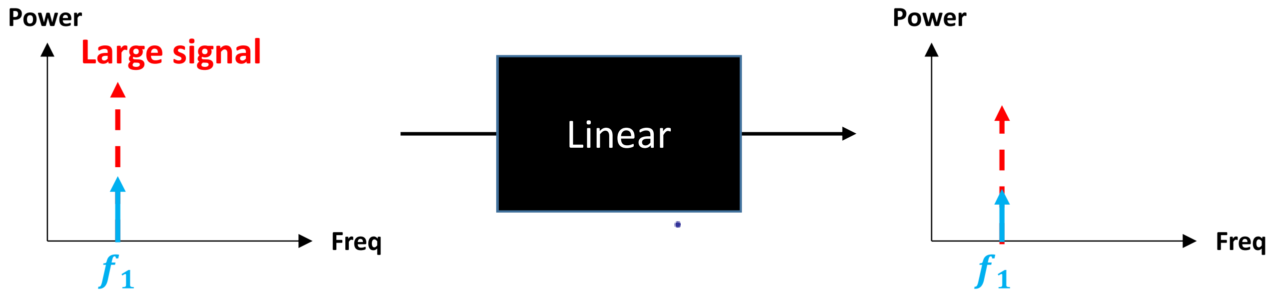

The response remains linear

I - Differences Active/Passive & Linear/Nonlinear

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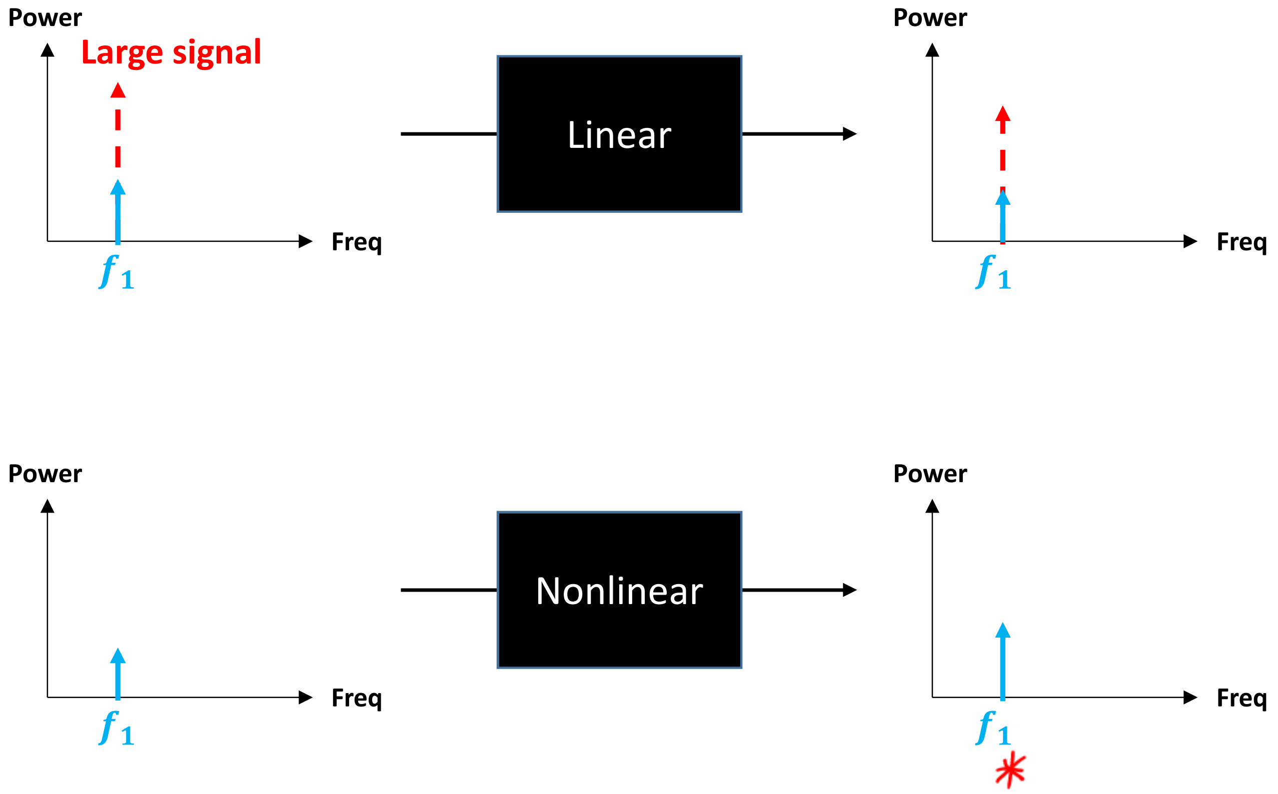

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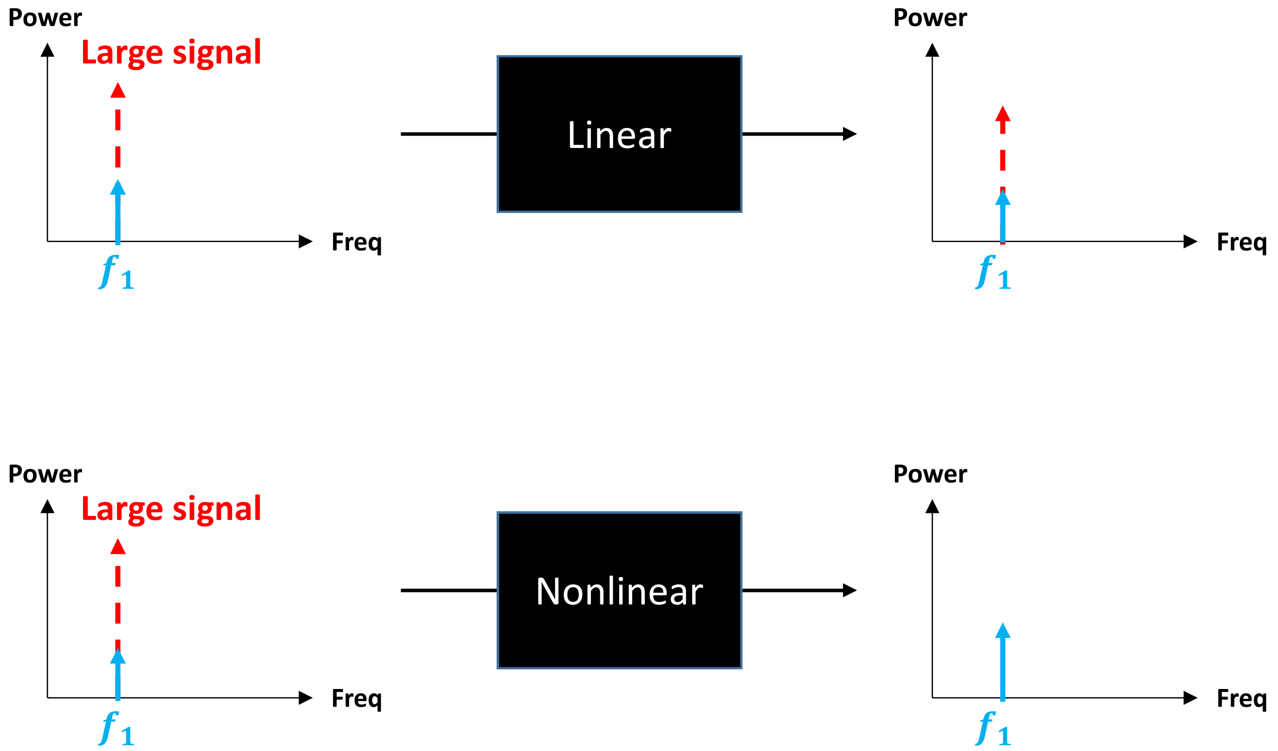

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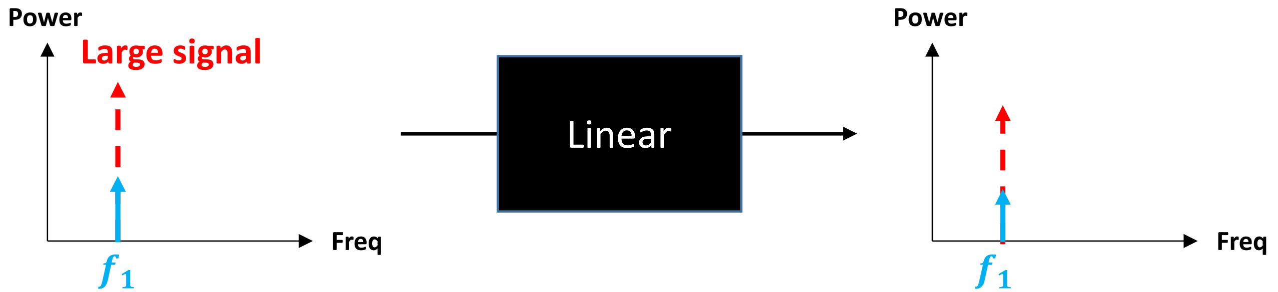
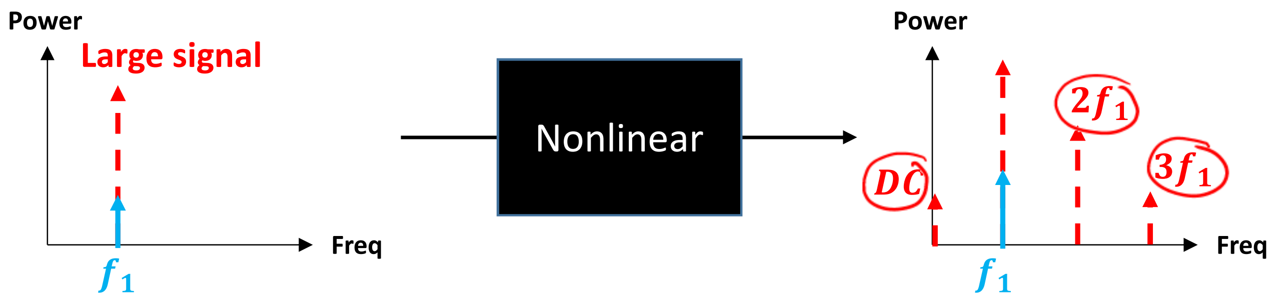


The response remains linear



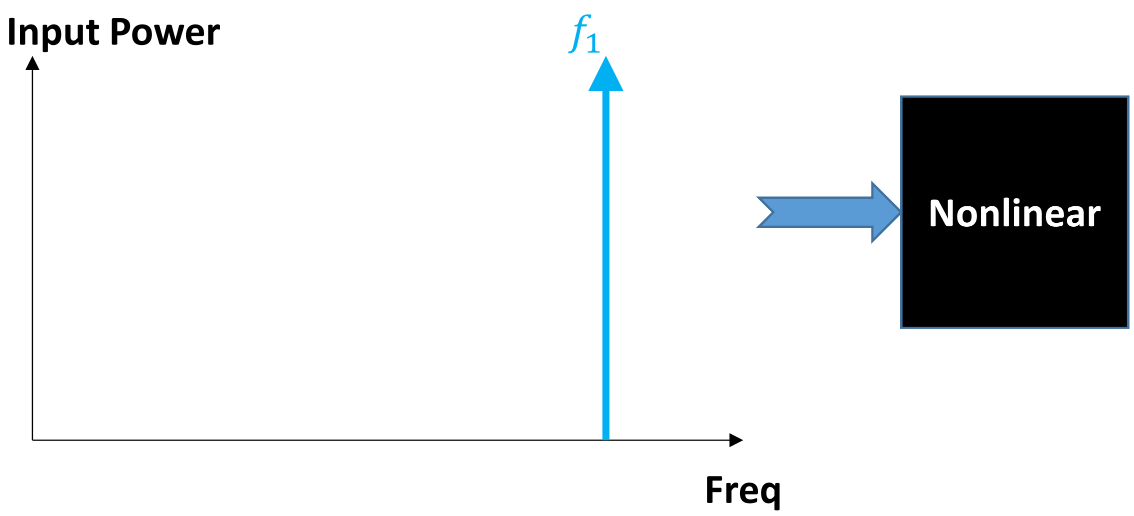
The response is nonlinear (generation of harmonics)

I - Differences Active/Passive & Linear/Nonlinear

3) Frequency generation of nonlinear devices (key property that enables communications (mixers…)

a) Single carrier

A single carrier f_1 in a 3rd order nonlinearity



I - Differences Active/Passive & Linear/Nonlinear

3) Frequency generation of nonlinear devices

a) Single carrier

Illustration using a 3rd order polynomial nonlinearity

$$x(t) = A\,cos(\omega_1 t) \Rightarrow \boxed{\textbf{Nonlinear}} \Rightarrow y(t) = a.x + b.x^2 + c.x^3$$

I - Differences Active/Passive & Linear/Nonlinear

3) Frequency generation of nonlinear devices

a) Single carrier

Illustration using a 3rd order polynomial nonlinearity

$$x(t) = A\,cos(\omega_1 t) \rightarrow \boxed{\textbf{Nonlinear}} \rightarrow y(t) = a.x + b.x^2 + c.x^3$$

Review:

$$cos(a+b) = \cos(a).\cos(b) - \sin(a).\sin(b)$$

$$cos(a-b) = \cos(a).\cos(b) + \sin(a).\sin(b)$$

$$\boxed{\cos(a).\cos(b) = \frac{1}{2}\cos(a+b) + \frac{1}{2}\cos(a-b)}$$

$$\rightarrow cos^2(x) = \frac{1}{2} + \frac{1}{2}\cos(2x) \rightarrow \boxed{cos^2(x) = \frac{1}{2}[1+\cos(2x)]}$$

You have to know these equations because they are often used to design nonlinear ciruits (mixers …)

$$\rightarrow cos^3(x) = \frac{1}{2}\cos(x) + \frac{1}{2}\cos(2x)\cos(x) = \frac{1}{2}\cos(x) + \frac{1}{4}\cos(3x) + \frac{1}{4}\cos(x) \rightarrow \boxed{cos^3(x) = \frac{3}{4}\cos(x) + \frac{1}{4}\cos(3x)}$$

I - Differences Active/Passive & Linear/Nonlinear

3) Frequency generation of nonlinear devices

a) Single carrier

Illustration using a 3rd order polynomial nonlinearity

$x(t) = A\,cos(\omega_1 t)$ → **Nonlinear** → $y(t) = \boxed{a.x} + b.x^2 + c.x^3$

$a.A\,cos(\omega_1 t)$

$$\cos(a).\cos(b) = \frac{1}{2}\cos(a+b) + \frac{1}{2}\cos(a-b)$$

$$cos^2(x) = \frac{1}{2}[1+\cos(2x)]$$

$$cos^3(x) = \frac{3}{4}\cos(x) + \frac{1}{4}\cos(3x)$$

$\cos^6(x) \longrightarrow 0 \quad 2 \quad 4 \quad 6$

I - Differences Active/Passive & Linear/Nonlinear

3) Frequency generation of nonlinear devices

a) Single carrier

Illustration using a 3rd order polynomial nonlinearity

$x(t) = A\cos(\omega_1 t)$ → **Nonlinear** → $y(t) = \boxed{a.x} + b.x^2 + c.x^3$

$a.A\cos(\omega_1 t)$

$$\cos(a).\cos(b) = \frac{1}{2}\cos(a+b) + \frac{1}{2}\cos(a-b)$$

$$\cos^2(x) = \frac{1}{2}[\underbrace{1}_{0} + \underbrace{\cos(2x)}_{2}] \quad *$$

$$\cos^3(x) = \frac{3}{4}\underbrace{\cos(x)}_{1} + \frac{1}{4}\underbrace{\cos(3x)}_{3}$$

Even Nonlinearity Order → Even Harmonics less than or equal to the order
Example of cos² (Nonlinearity Order 2 → Harmonics 0 and 2)

Odd Nonlinearity Order → Odd Harmonics less than or equal to the order
Example of cos³ (Nonlinearity Order 3 → Harmonics 3 and 1)

→ **Without calculation of cos⁴, we know that a nonlinearity order of 4 → Harmonics 4, 2 and 0**
Without calculation of cos⁵, we know that a nonlinearity order of 5 → Harmonics 5, 3 and 1

I - Differences Active/Passive & Linear/Nonlinear

3) Frequency generation of nonlinear devices

a) Single carrier

Illustration using a 3rd order polynomial nonlinearity

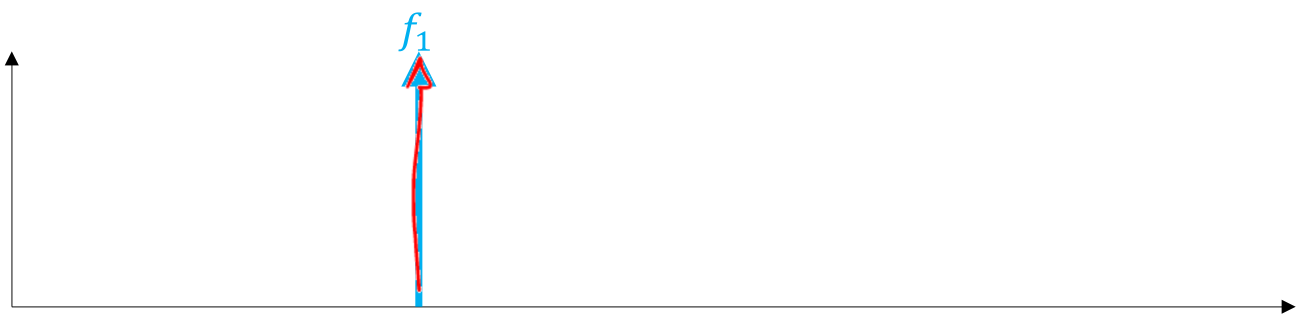
$$x(t) = A\,cos(\omega_1 t) \Rightarrow \boxed{\textbf{Nonlinear}} \Rightarrow y(t) = \boxed{a.x} + b.x^2 + c.x^3$$

$$a.A\,cos(\omega_1 t)$$ **1st order of nonlinearity → Harmonic 1**

$$\cos(a).\cos(b) = \frac{1}{2}\cos(a+b) + \frac{1}{2}\cos(a-b)$$

$$cos^2(x) = \frac{1}{2}[1+\cos(2x)]$$

$$cos^3(x) = \frac{3}{4}\cos(x) + \frac{1}{4}\cos(3x)$$



I - Differences Active/Passive & Linear/Nonlinear

3) Frequency generation of nonlinear devices

a) Single carrier

Illustration using a 3rd order polynomial nonlinearity

$x(t) = A\,cos(\omega_1 t)$ → **Nonlinear** → $y(t) = a.x + \boxed{b.x^2} + c.x^3$

$$\overset{0}{\frac{b.A^2}{2}} + \frac{b.A^2}{2}\overset{2f_1}{cos(2\omega_1 t)}$$

$$\cos(a).\cos(b) = \frac{1}{2}\cos(a+b) + \frac{1}{2}\cos(a-b)$$

$$cos^2(x) = \frac{1}{2}[1+\cos(2x)]$$

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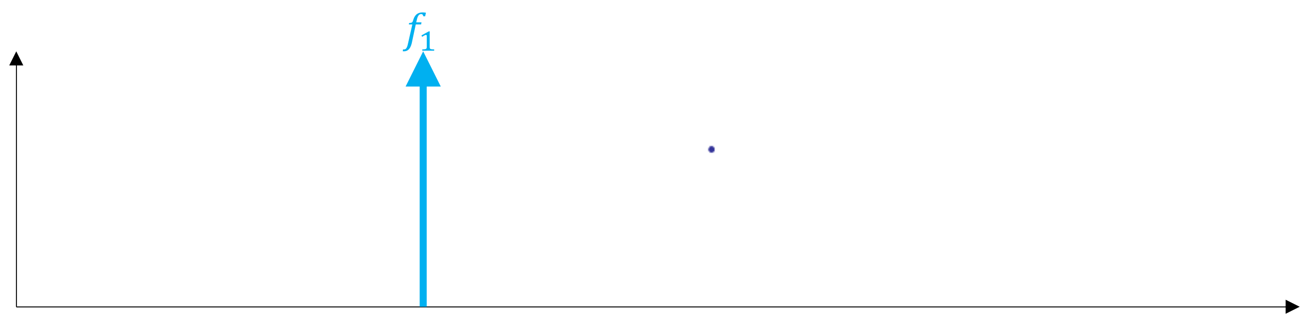


I - Differences Active/Passive & Linear/Nonlinear

3) Frequency generation of nonlinear devices

a) Single carrier

Illustration using a 3rd order polynomial nonlinearity

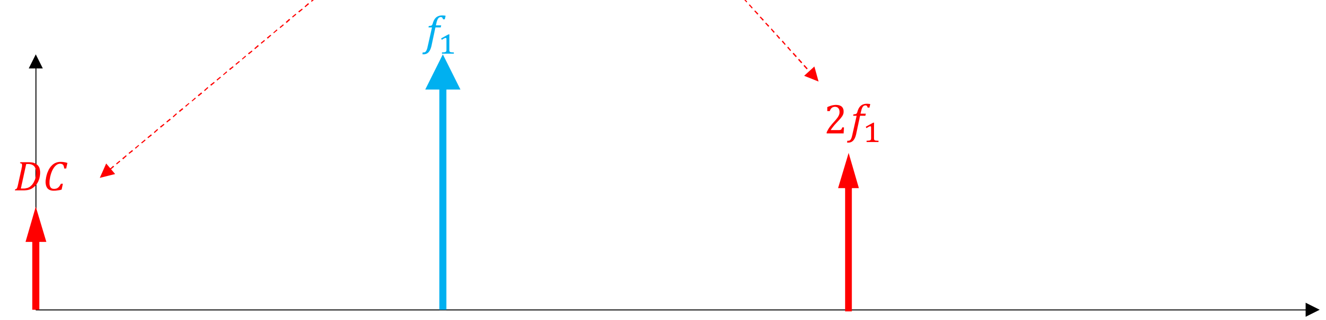
$$x(t) = A\,cos(\omega_1 t) \rightarrow \textbf{Nonlinear} \rightarrow y(t) = a.x + \boxed{b.x^2} + c.x^3$$

$$\cos(a).\cos(b) = \frac{1}{2}\cos(a+b) + \frac{1}{2}\cos(a-b)$$

$$\frac{b.A^2}{2} + \frac{b.A^2}{2}cos(2\omega_1 t)$$

2nd order of nonlinearity
→ Harmonics 0 and 2

$$cos^2(x) = \frac{1}{2}[1 + \cos(2x)]$$



$$cos^3(x) = \frac{3}{4}\cos(x) + \frac{1}{4}\cos(3x)$$

I - Differences Active/Passive & Linear/Nonlinear

3) Frequency generation of nonlinear devices

a) Single carrier

Illustration using a 3rd order polynomial nonlinearity

$$x(t) = A\,cos(\omega_1 t) \rightarrow \boxed{\text{Nonlinear}} \rightarrow y(t) = a.x + b.x^2 + \boxed{c.x^3}$$

f_1 $3f_1$

$$\frac{3c.A^3}{4}cos(\omega_1 t) + \frac{c.A^3}{4}cos(3\omega_1 t)$$

$$\boxed{\cos(a).\cos(b) = \frac{1}{2}\cos(a+b) + \frac{1}{2}\cos(a-b)}$$

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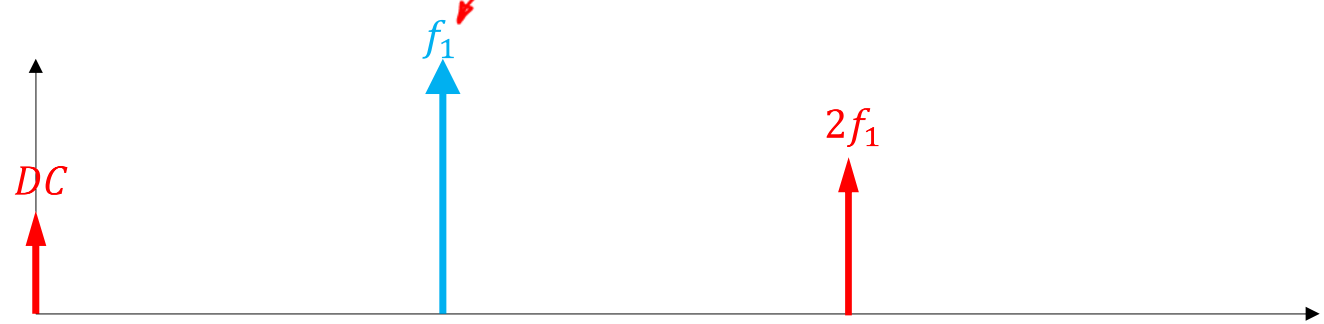

I - Differences Active/Passive & Linear/Nonlinear

3) Frequency generation of nonlinear devices

a) Single carrier

Illustration using a 3rd order polynomial nonlinearity

$x(t) = A\,cos(\omega_1 t)$ → **Nonlinear** → $y(t) = a.x + b.x^2 + \boxed{c.x^3}$

$$\frac{3c.A^3}{4} cos(\omega_1 t) + \frac{c.A^3}{4} cos(3\omega_1 t)$$

3rd order of nonlinearity
→ Harmonics 1 and 3

$$\cos(a).\cos(b) = \frac{1}{2}\cos(a+b) + \frac{1}{2}\cos(a-b)$$

$$cos^2(x) = \frac{1}{2}[1 + \cos(2x)]$$

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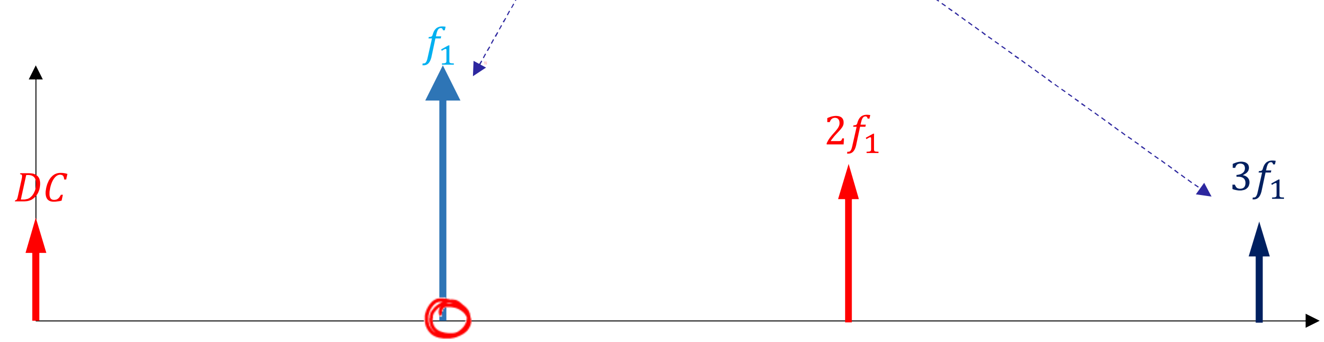
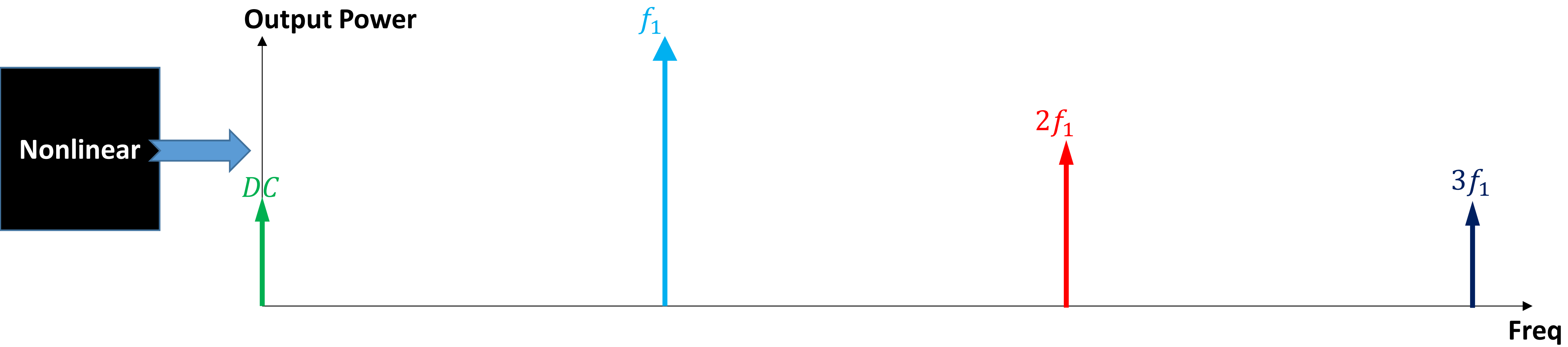


I - Differences Active/Passive & Linear/Nonlinear

3) Frequency generation of nonlinear devices

a) Single carrier

A single carrier f_1 in a nth order nonlinearity → **harmonics** $\boldsymbol{pf_1}$ ***with*** $\boldsymbol{p \le n}$



I - Differences Active/Passive & Linear/Nonlinear

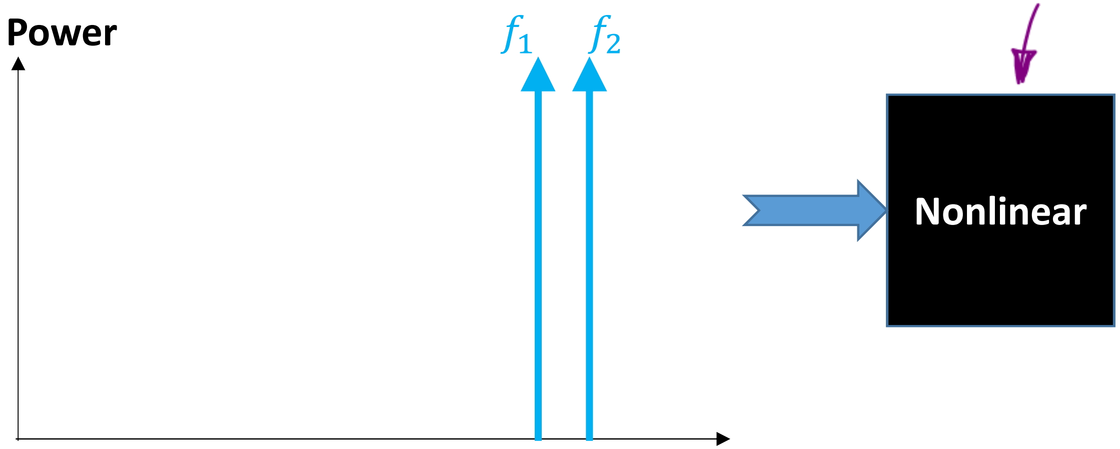
3) Frequency generation of nonlinear devices

b) Multiple carriers (**example of two carriers → intermodulation products or mixing products**)

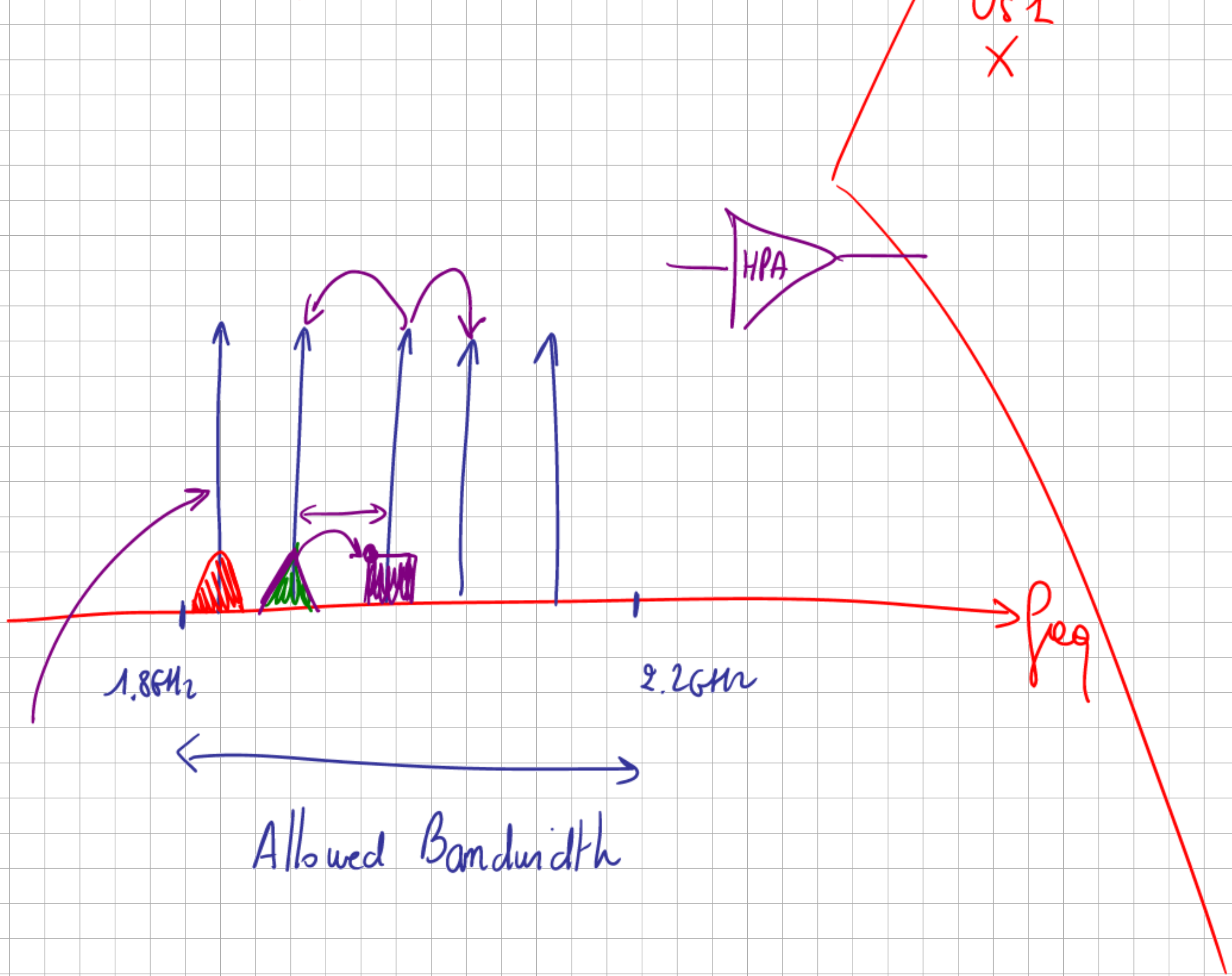
disadvantage for amplifiers — required for mixers

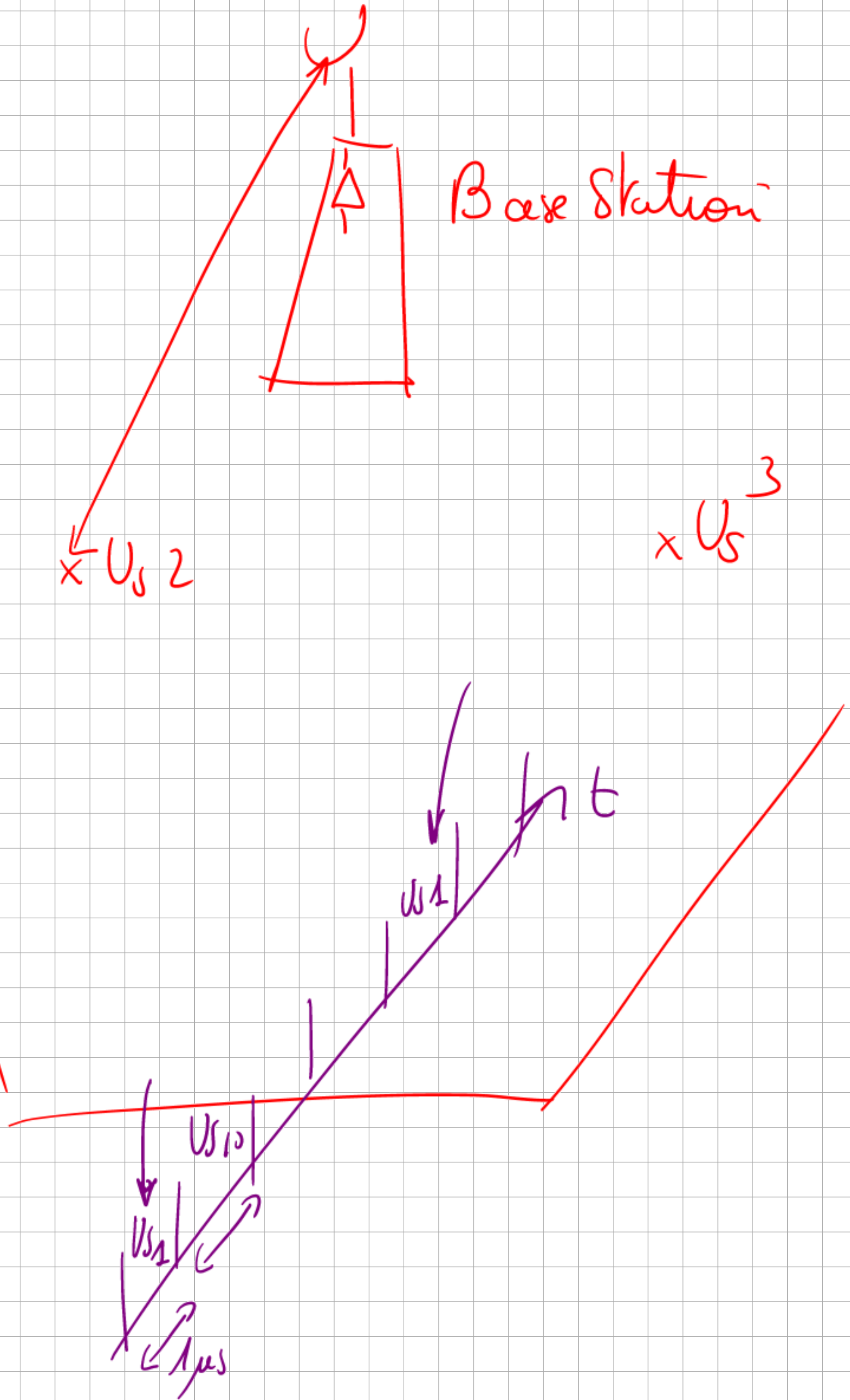
Two carriers f_1 and f_2 in a 3rd order nonlinearity

$$y = ax + bx^2 + cx^3$$



Multiple Access

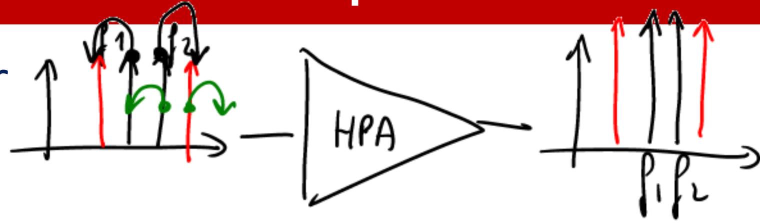




FDMA (Frequency Division MA)

TDMA (Time ______)

I - Differences Active/Passive & Linear/Nonlinear



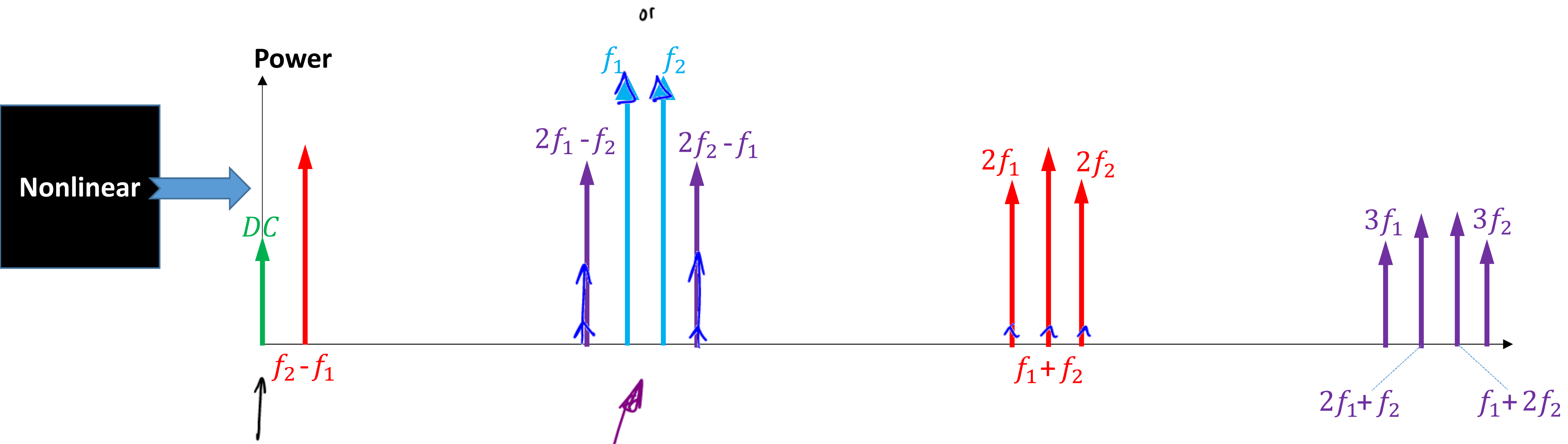
3) Frequency generation of nonlinear devices

b) Multiple carriers (**example of two carriers → intermodulation products**)

Two carriers f_1 and f_2 in a 3[rd] order nonlinearity → **intermodulation products** $(\pm p f_1 \pm q f_2)$ *with* $\max(p+q) \leq 3$

$f_1\ f_2 - \boxed{NL} \rightarrow \pm p f_1 \pm q f_2$ $(p+q)$ = intermodulation order

$(p+q)$ is the order of nonlinearity



max $(p+q) \leq 3$

max $(p+q) \leq 5$

f_1 & f_2 $\qquad \pm p f_1 \pm q f_2 \qquad p+q \leq 3 \qquad f_2 > f_1$

If $p=0$ $\quad q=0,1,2,3 \rightarrow f_2,\ 2f_2,\ 3f_2,\ DC$

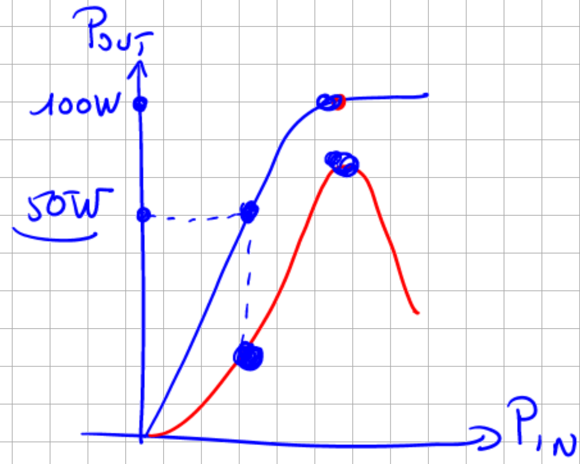
If $p=1$ $\quad q=0,1,2 \rightarrow f_1,\ f_1+f_2,\ f_1+2f_2$

$\underbrace{f_2-f_1}$ $\quad 2f_2-f_1$

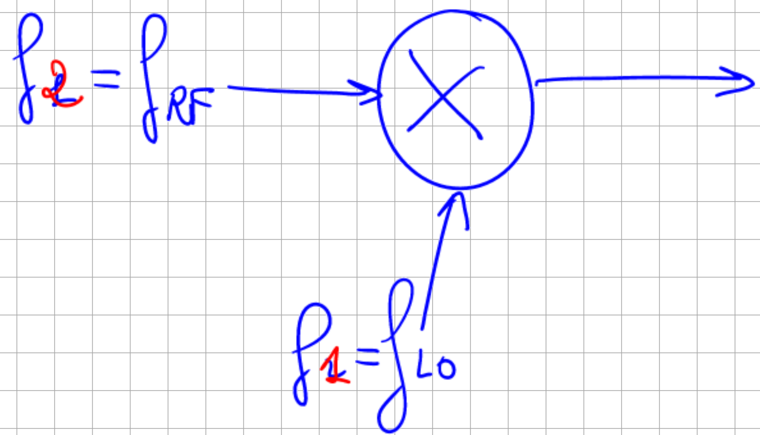
If $p=2$ $\quad q=0,1 \rightarrow 2f_1,\ 2f_1+f_2$

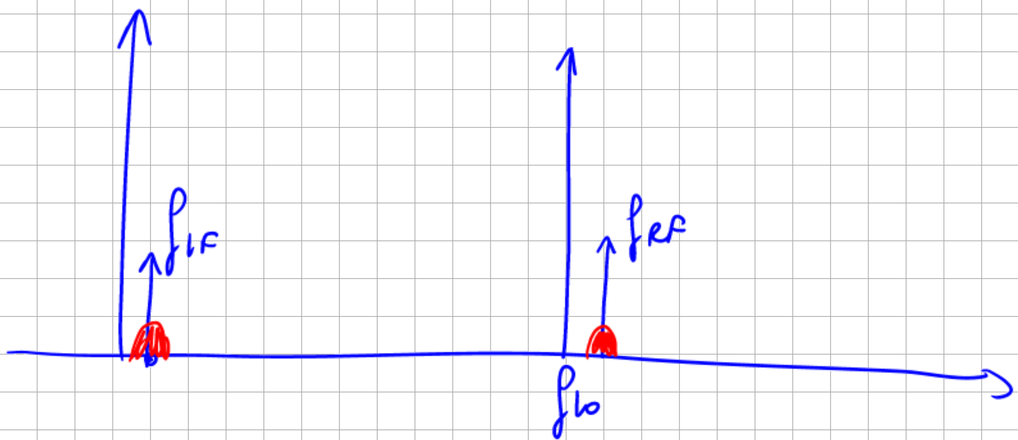
$2f_1-f_2$

If $p=3$ $\quad q=0 \rightarrow 3f_1$



$f_2 - f_1$





I - Differences Active/Passive & Linear/Nonlinear

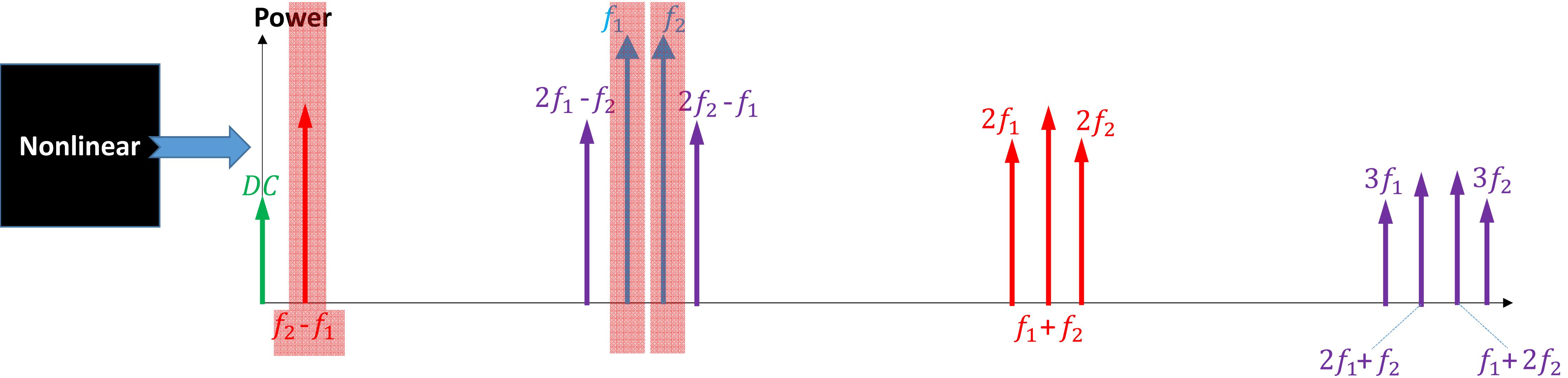
3) Frequency generation of nonlinear devices

b) Multiple carriers (**example of two carriers → intermodulation products**)

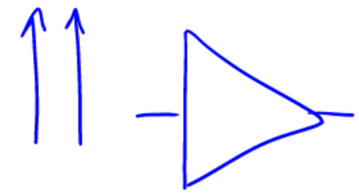
Two carriers f_1 and f_2 in a 3rd order nonlinearity → **intermodulation products** $(\pm \boldsymbol{p} \boldsymbol{f}_1 \pm \boldsymbol{q} \boldsymbol{f}_2)$ $with \quad \max(p+q) \leq 3$

$(p+q)$ is the order of nonlinearity

2nd order intermodulation (IM2) → Mixing Function (IF, LO, RF)
→ Frequency doublers



I - Differences Active/Passive & Linear/Nonlinear



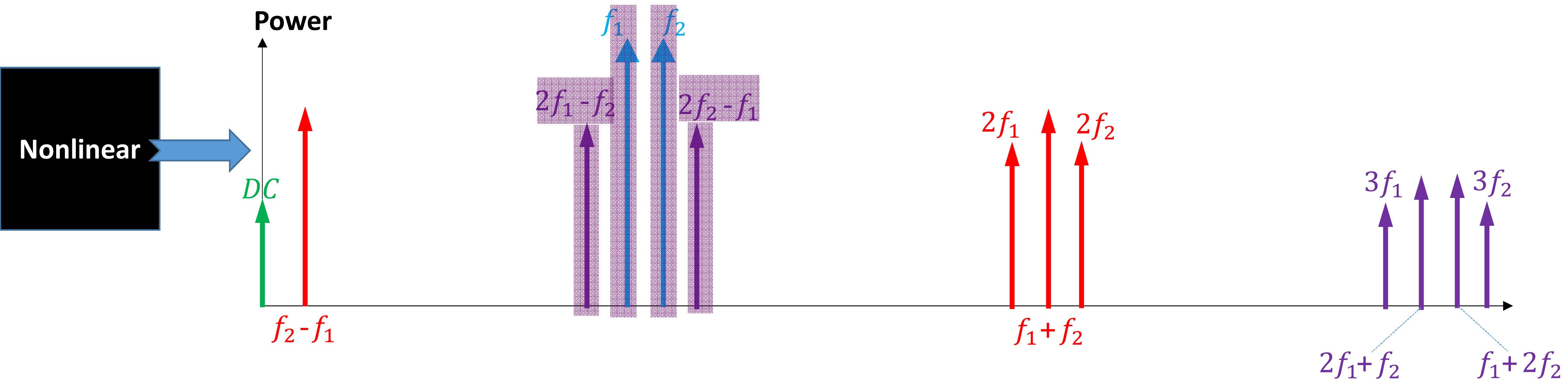
3) Frequency generation of nonlinear devices

b) Multiple carriers (**example of two carriers → intermodulation products**)

Two carriers f_1 and f_2 in a 3rd order nonlinearity → **intermodulation products** $(\pm \boldsymbol{p f_1} \pm \boldsymbol{q f_2})$ *with* $\max(p+q) \leq 3$

$(p+q)$ is the order of nonlinearity

3rd order intermodulation (IM3) → Critical for multiple access



II – Brief Overview of High-Frequency Active Devices for Power Amplifiers

< 1 GHz

1) Low Frequency (up to 100MHz)
   - Well established consumer electronics / High level of integration / Low cost / High volumes
   - Silicon Bipolar Transistors / MOSFETs (Metal Oxyde Semiconductor FETs / BiCMOS ...)

Bipolar and CMOS on the same wafer

2) Radio Frequency (up to 2-3 GHz)
   - Silicon LDMOS (Laterally Diffused MOSFETs to reach high powers @ RF
   - GaAs MESFETs (Metal Semiconductor FETs)
   - GaAs HBTs (Heterojunction Bipolar Transistors)
   - GaAs HEMTs (High Electron Mobility Transistors)

LDMOS

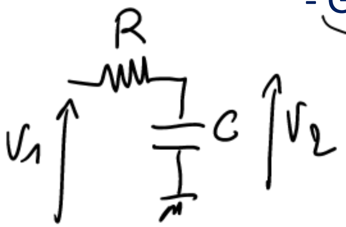
cutoff

3) High Frequency (up to 100 GHz)
   - GaAs HEMTs and HBT
   - GaN HEMTs

$$\omega_c = \frac{1}{RC}$$

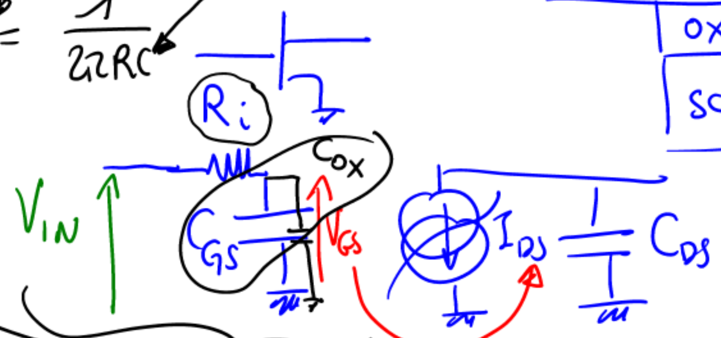
$$f_c = \frac{1}{2\pi RC}$$

Contact = Metal Oxyde FET



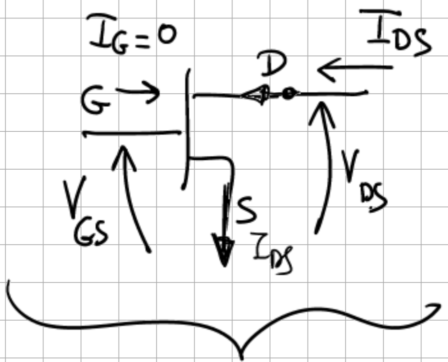
$$\left|\frac{V_2}{V_1}\right| = \frac{1}{\sqrt{1+\left(\frac{\omega}{\omega_c}\right)^2}}$$

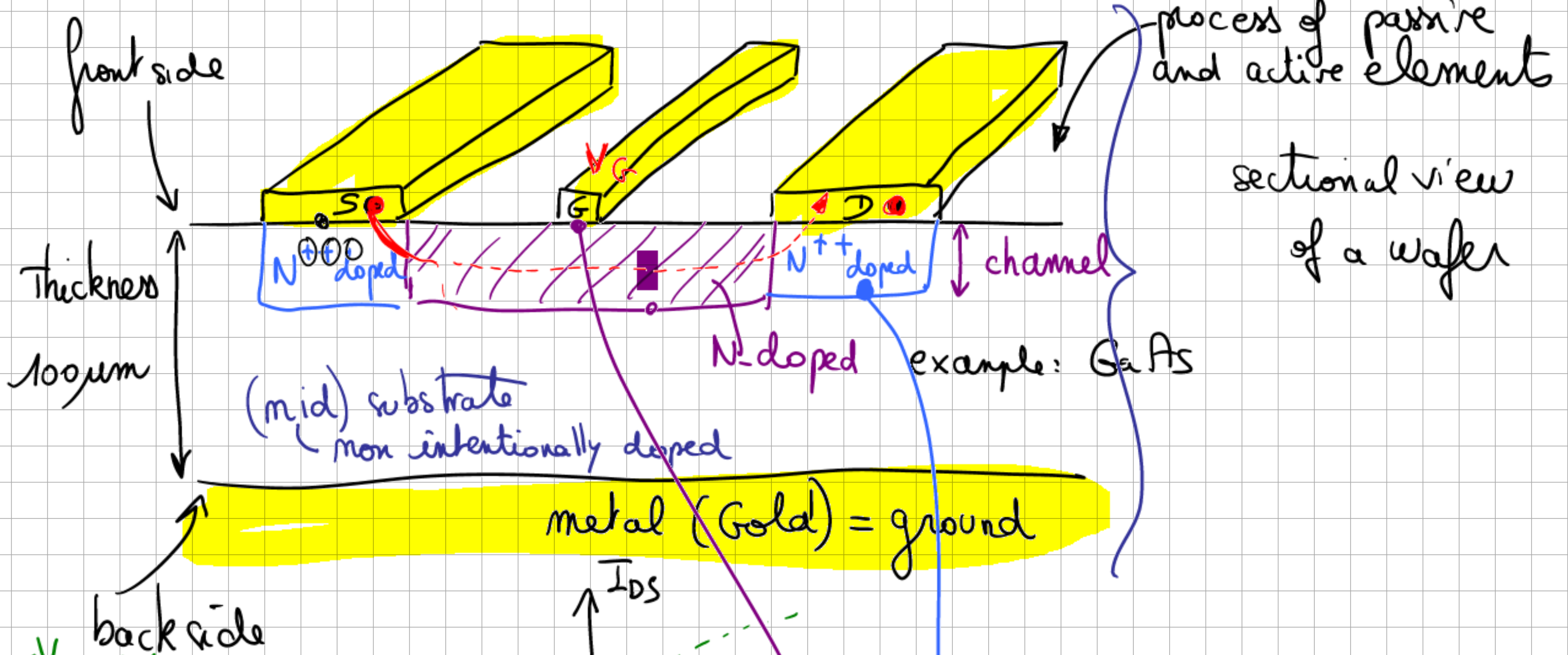
$$\frac{V_2}{V_1} = \frac{1/jC\omega}{R+1/jC\omega} = \frac{1}{1+jRC\omega}$$

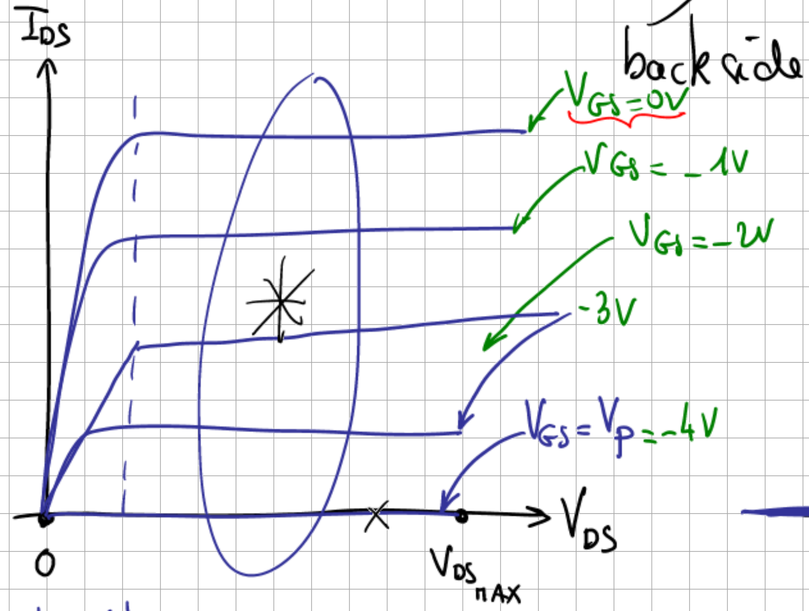


$$f_{c\,MOSFET} \ll$$

MESFET

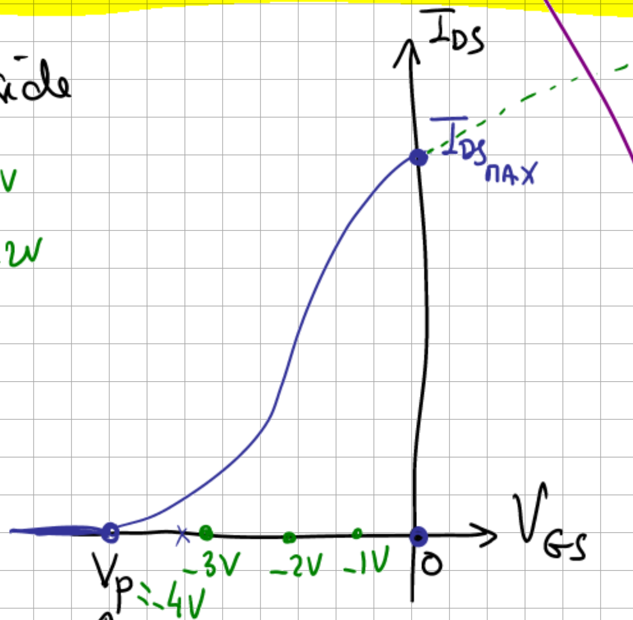


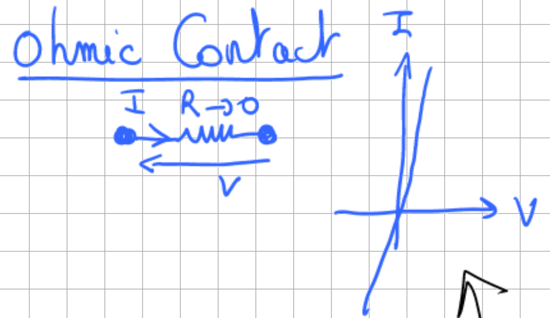


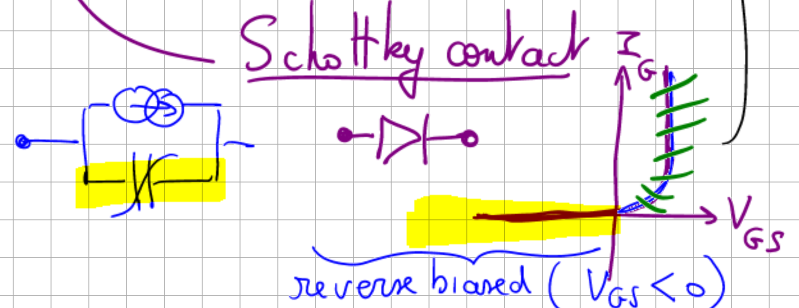


Ohmic Region
$V = RI$
MIXERS

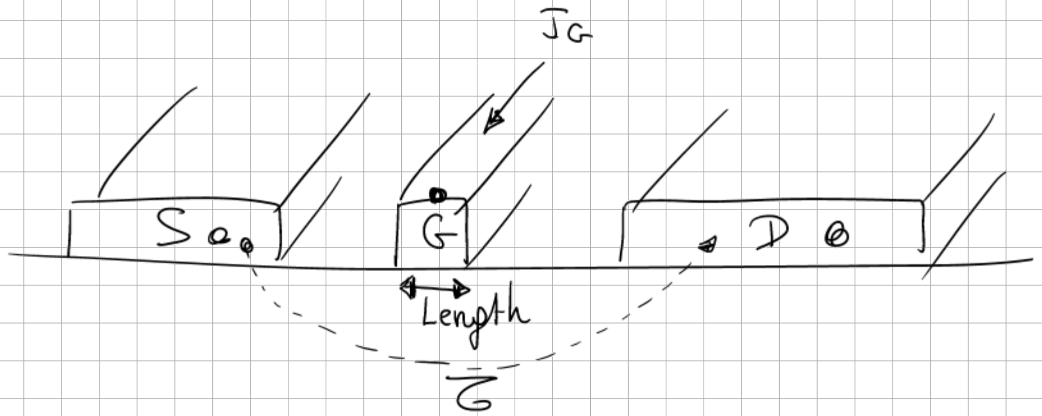
Saturated Region
$I_{DS} \simeq f(V_{GS})$
power amplifiers





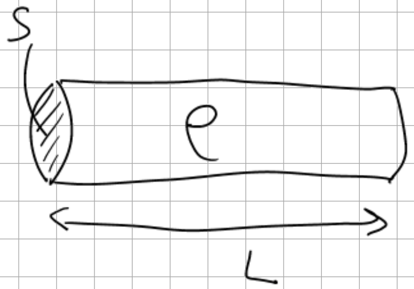


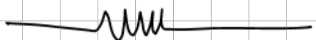
$$v = \frac{d}{t}$$



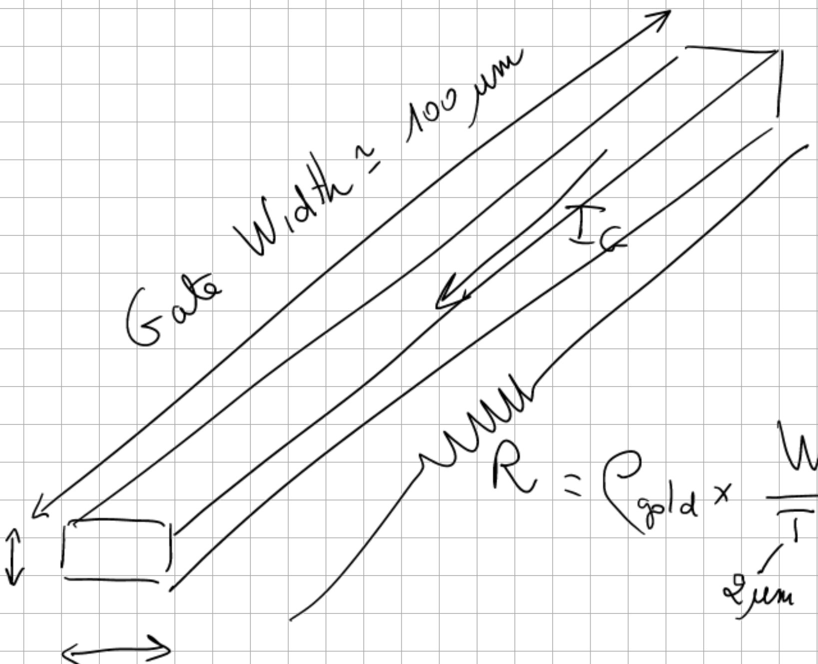
$$\tau = \frac{d}{v_x} \simeq \frac{L_G}{v}$$

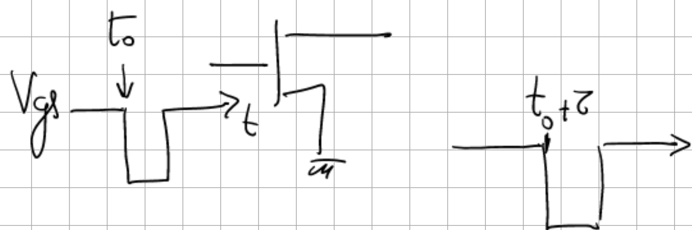
μ_n





$$R = \rho \times \frac{L}{S}$$





T

100 μm

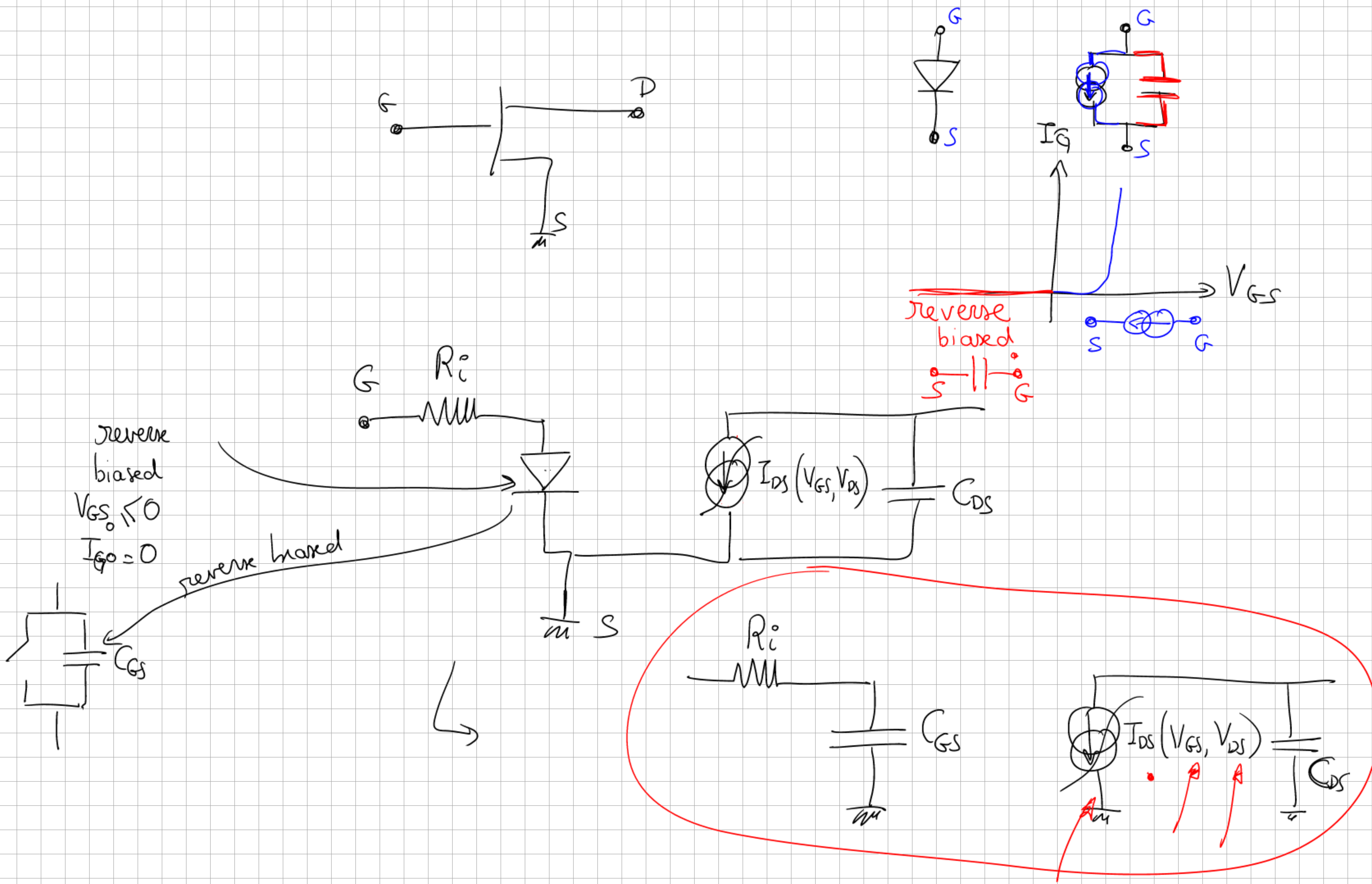
$$R = \rho_{gold} \times \frac{W_g}{T \times L_g}$$

2 μm   0.5 μm

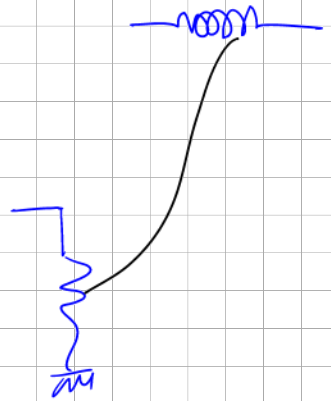
low freq transistor $\tau >>$

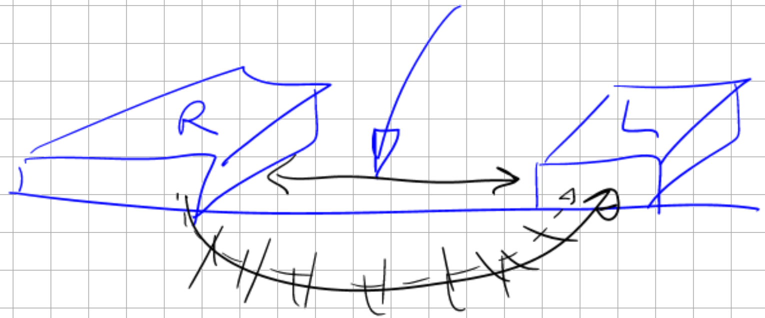
$$P_{DISS} = R I_{DC}^2$$

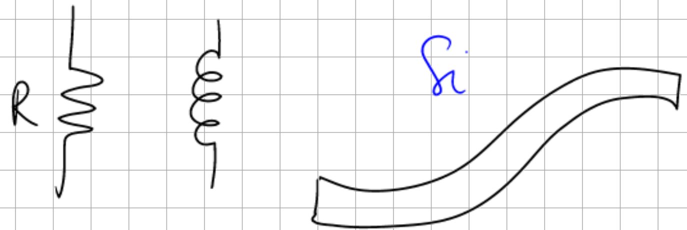
Gate Length ≃ 0.5 μm   0.1 μm



G
D
S
G
S
G
S
I_G
V_{GS}
reverse biased
S
G
S
G
G
R_i
reverse biased
$V_{GS_0} \leq 0$
$I_{G0} = 0$
reverse biased
$I_{DS}(V_{GS}, V_{DS})$
C_{DS}
S
C_{GS}
R_i
C_{GS}
$I_{DS}(V_{GS}, V_{DS})$
C_{DS}







Si

GaAs

Insulator $\longleftarrow$ Semi-Conductor $\longrightarrow$ Conductor

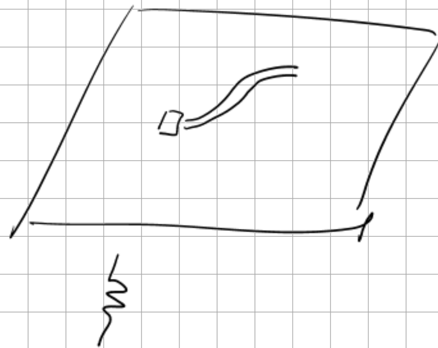
GaAs = semi-insulating substrate

Si = Semi-conductor substrate

$$\mathrm{Dim}(\text{Circuit}) \ll \lambda = \frac{v}{f}$$

$$\geq$$

$$v \rightarrow \frac{c}{\sqrt{\varepsilon_r}}$$

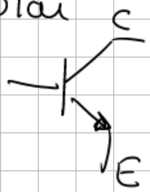


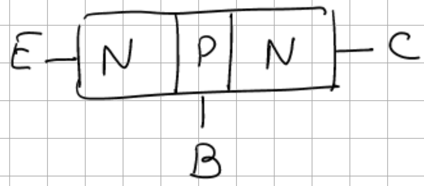
⊛ HBT (Heterojunction Bipolar Transistors)

Metal - N contact FET

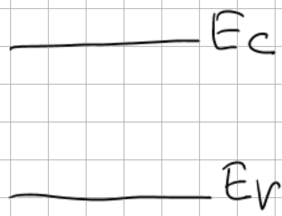
PN contact bipolar

Bipolar

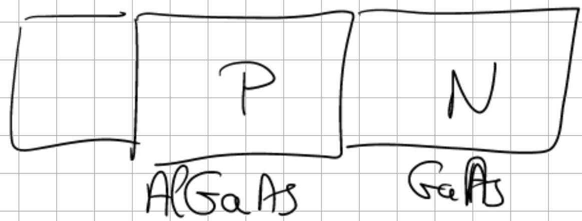




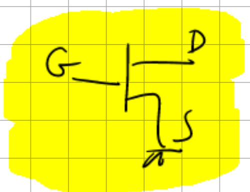
bandgap



Two semi-conductors with ≠ bandgaps



⊛ HEMT (High Electron Mobility Transistor)



MESFET (channel is N-doped → $\mu_n \downarrow$

HEMT (channel is not doped) → $\mu_n \uparrow$

AlGaAs / GaAs   GaAs

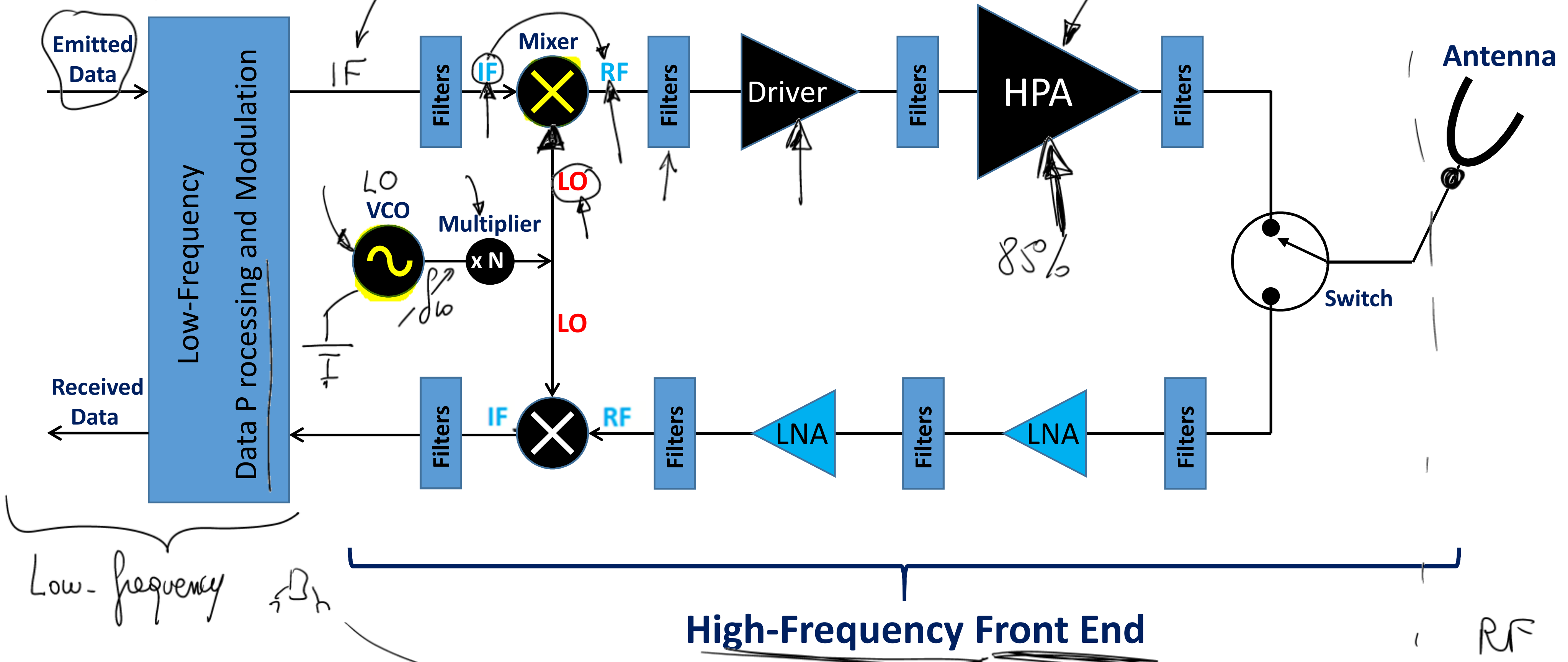
AlGaN / GaN = "GaN HEMT"

III – High-Frequency Active Circuits in Communication Systems

intermediate frequency

High Power Amplifier

1) Example (Simplified Block Diagram of E/R Functions)



Low-frequency

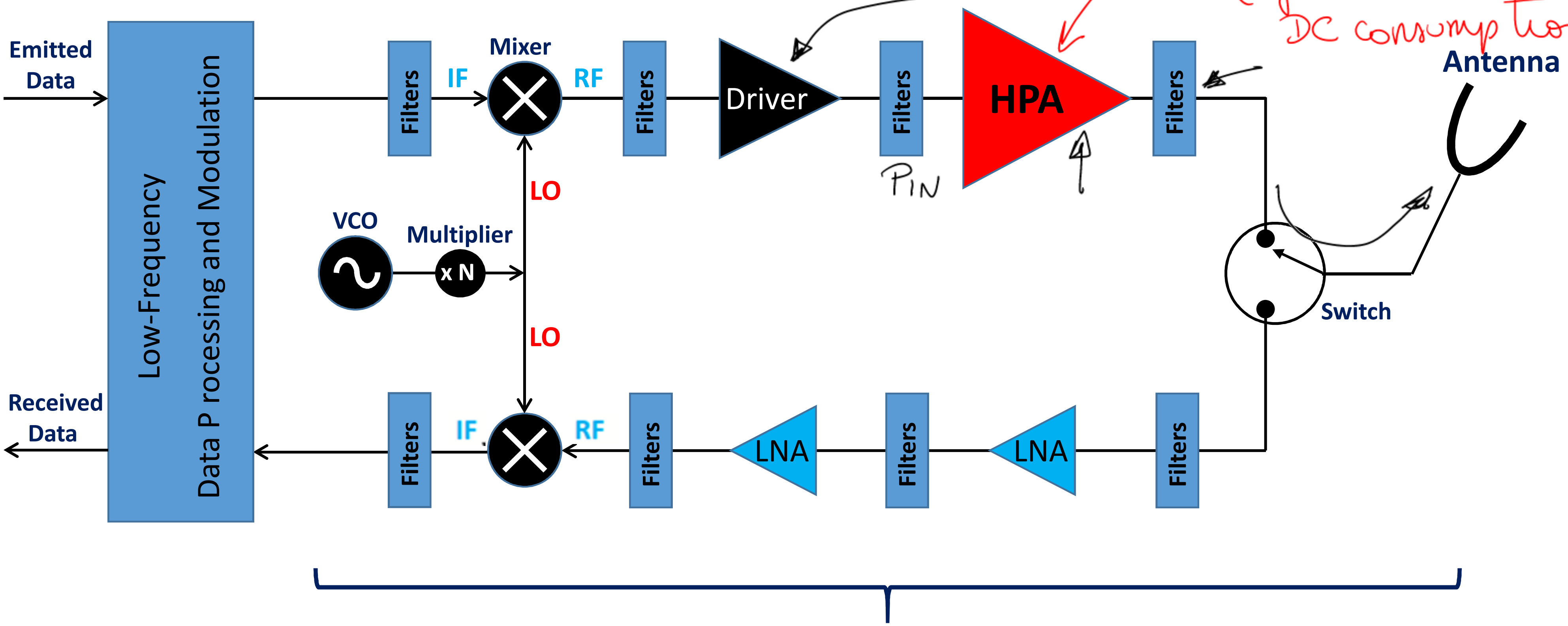
RF
=
(2 – 4) GHz
10 GHz

III – High-Frequency Active Circuits in Communication Systems

2) Main High-Frequency Active Circuits

a) **Amplifiers (HPA : High Power Amplifier)**

HPA (more than 80% of total DC consumption)

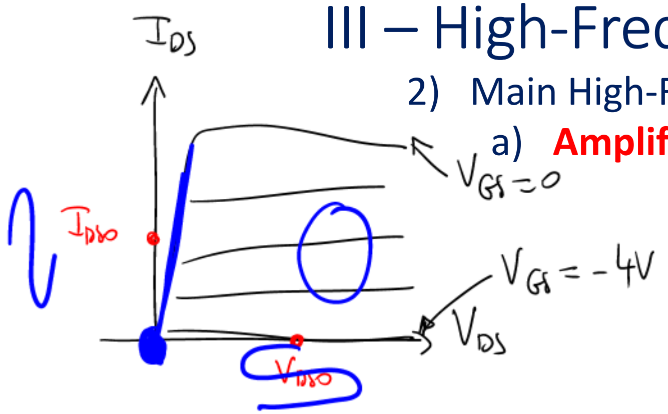


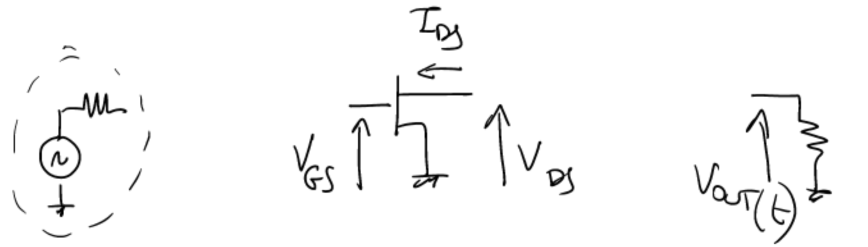
High-Frequency Front End

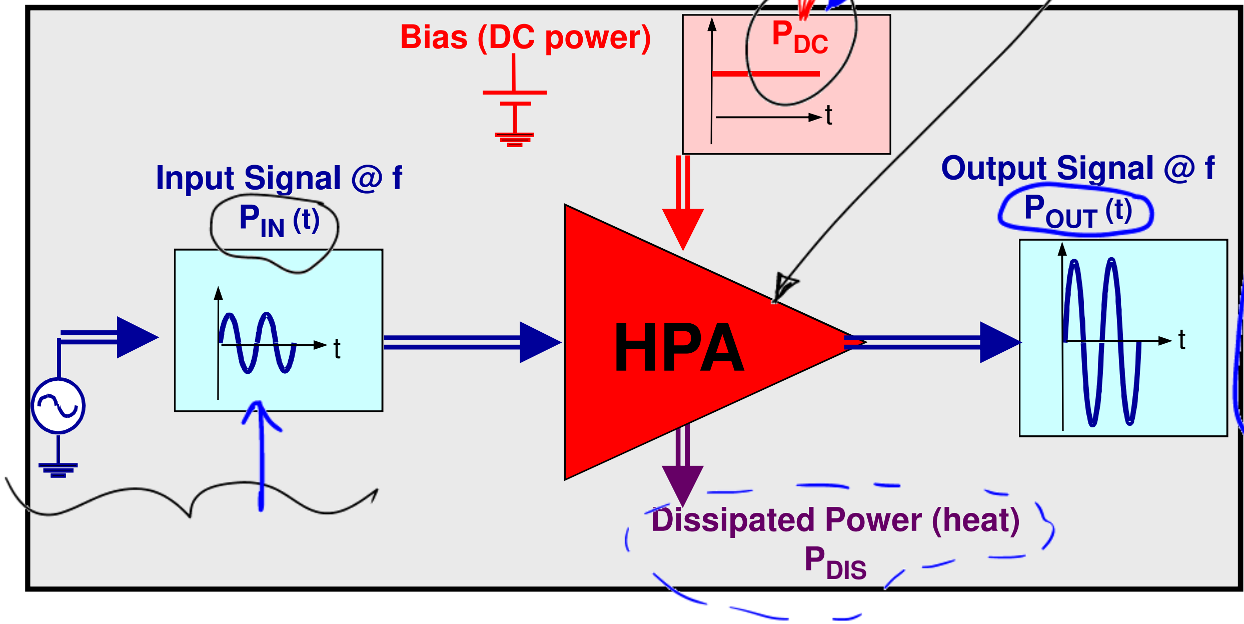
III – High-Frequency Active Circuits in Communication Systems

2) Main High-Frequency Active Circuits

a) Amplifiers (HPA : High Power Amplifier)







$\sum$ Input Powers $=$ $\sum$ Output Powers

$P_{IN} + P_{DC} = P_{OUT} + P_{DIS}$

Power gain and **Power Added Efficiency**

$\boxed{G = P_{OUT} / P_{IN}}$ and $\boxed{PAE = (P_{OUT} - P_{IN}) / P_{DC}}$

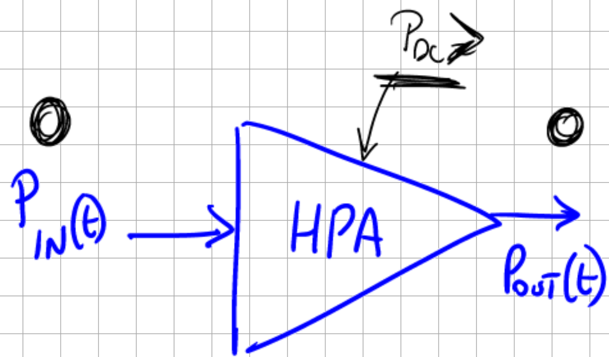
$\rightarrow P_{DIS} = P_{DC} - (P_{OUT} - P_{IN}) = P_{DC} - PAE \, . \, P_{DC}$

Dissipated Power

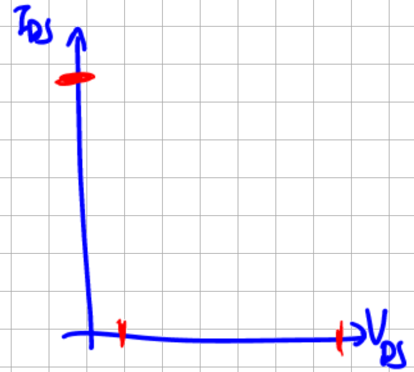
$\rightarrow P_{DIS} = P_{DC} (1 - PAE)$

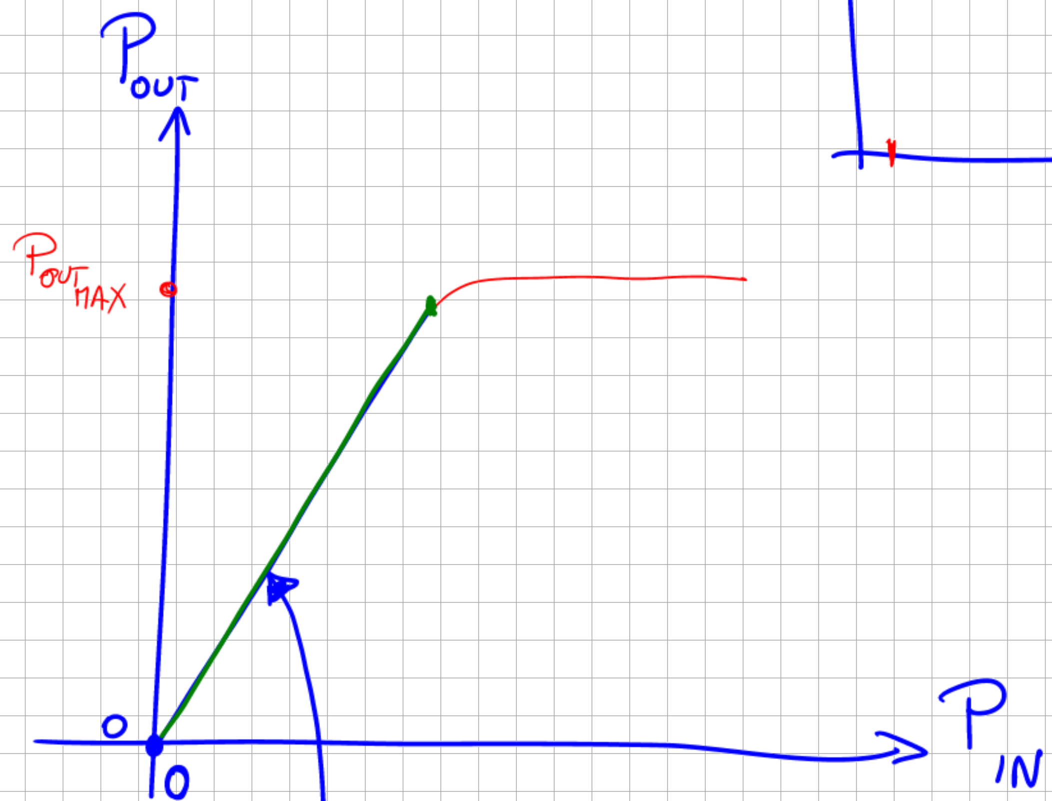
Temperature

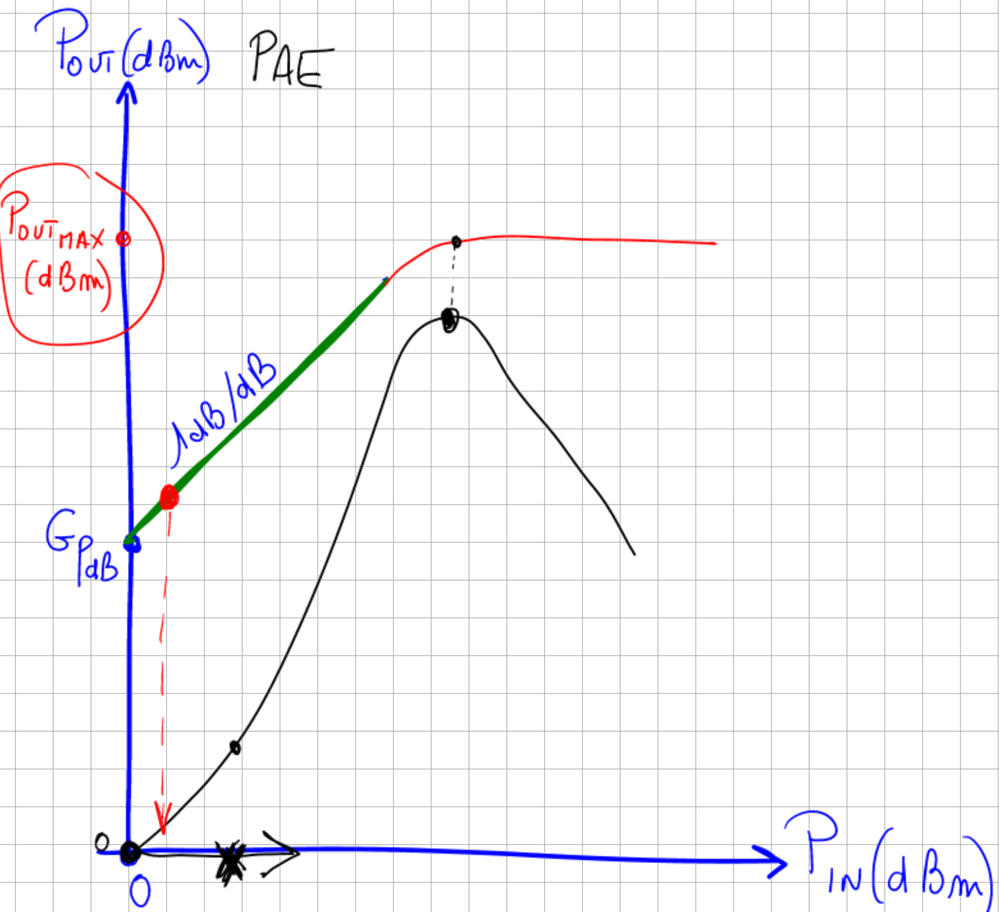
$T \sim P_{DIS}$



$$P_{DIS} = P_{DC}\left(1 - PAE\right)$$







linear region before saturation

$$\boxed{P_{OUT} = G_p \times P_{IN}}$$

$$P_{OUT}(dBm) = 10\log\left(P_{OUT}(mW)\right)$$

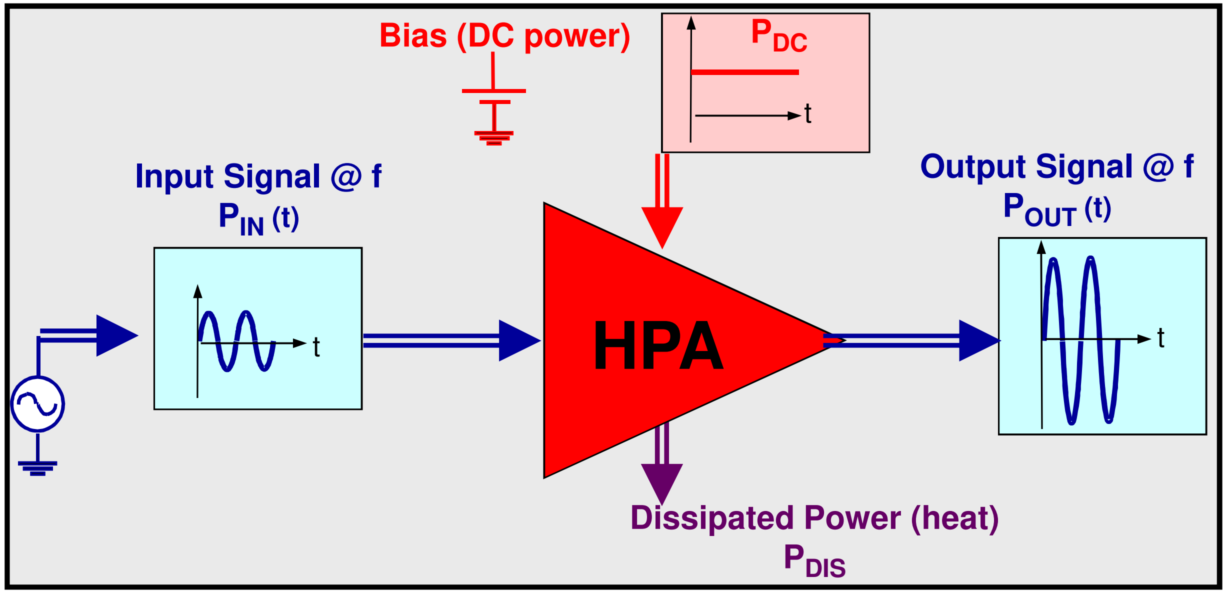
$$G_p(dB) = 10\log\left(G_p\right)$$

$$\boxed{P_{OUT}(dBm) = P_{IN}(dBm) + G_p(dB)}$$

III – High-Frequency Active Circuits in Communication Systems

2) Main High-Frequency Active Circuits

a) Amplifiers (HPA : High Power Amplifier)



Standard

Only one accurate definition of efficiency

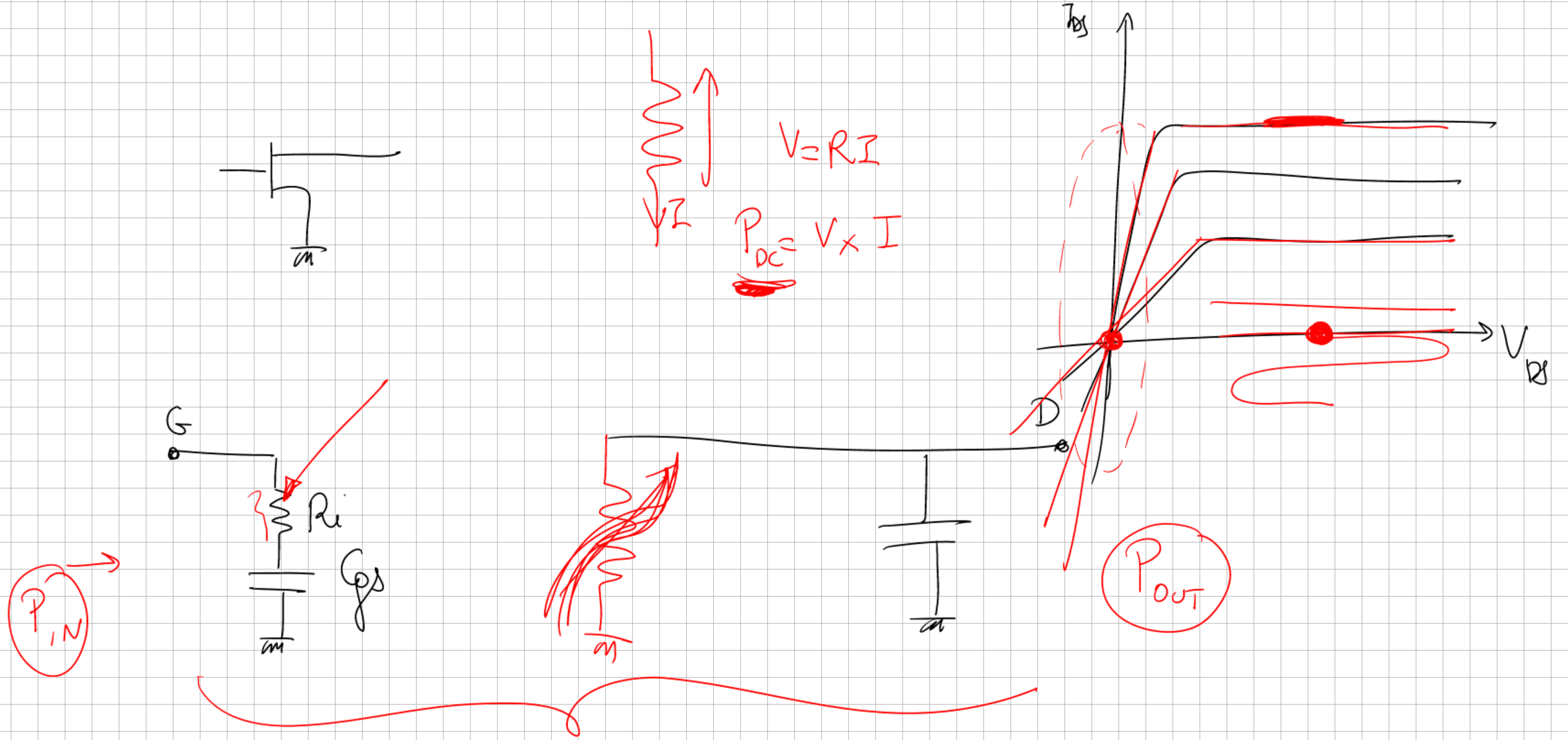
(same value at low-frequency because of higher gain)

Power Efficiency

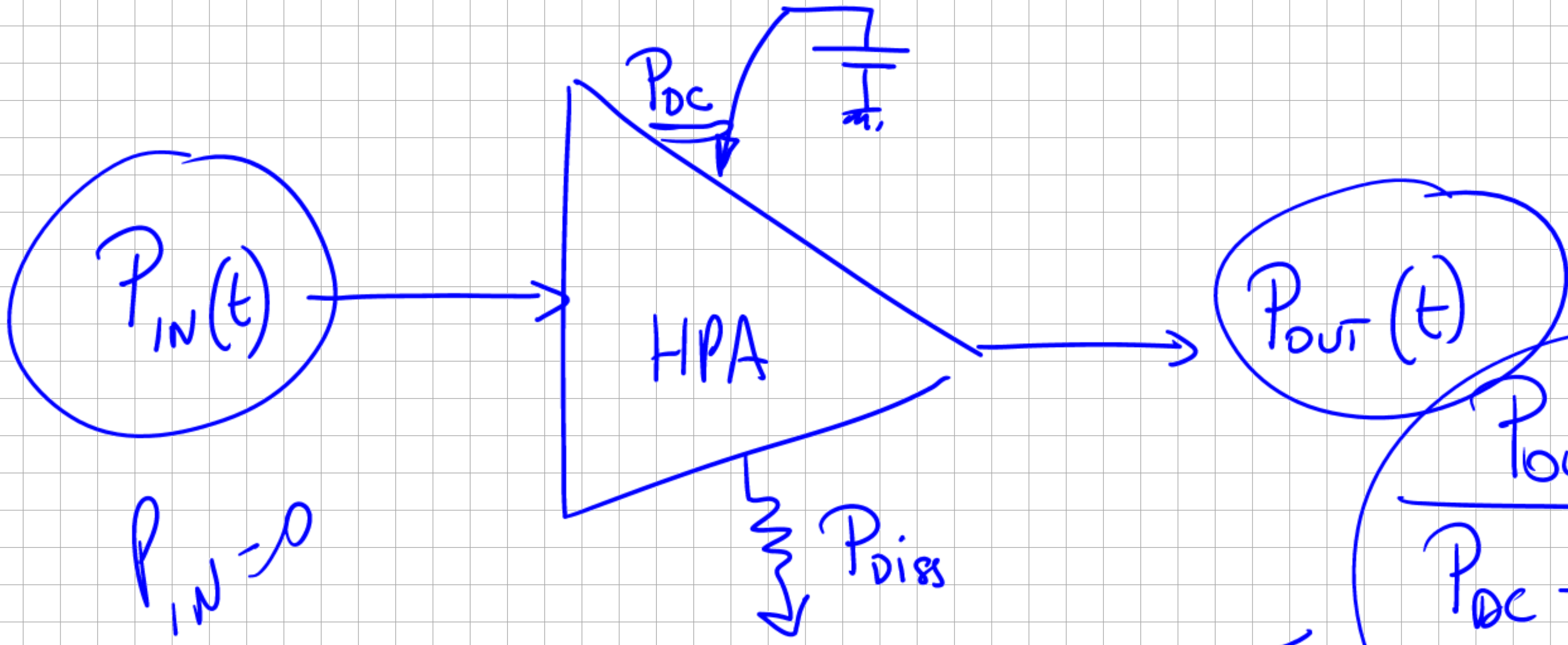
$$\eta = P_{OUT} / P_{DC}$$

Power Added Efficiency

$$\textbf{PAE} = (P_{OUT} - P_{IN}) / P_{DC}$$



V = RI
P_DC = V x I
I_DS
V_DS
G
D
Ri
Cgs
P_IN
P_OUT



η

$P_{IN} = 0$

$$\frac{P_{OUT}}{P_{DC} + P_{IN}}$$

standard efficiency $\cancel{\eta = \frac{P_{OUT}(t)}{P_{DC}}}$

PAE

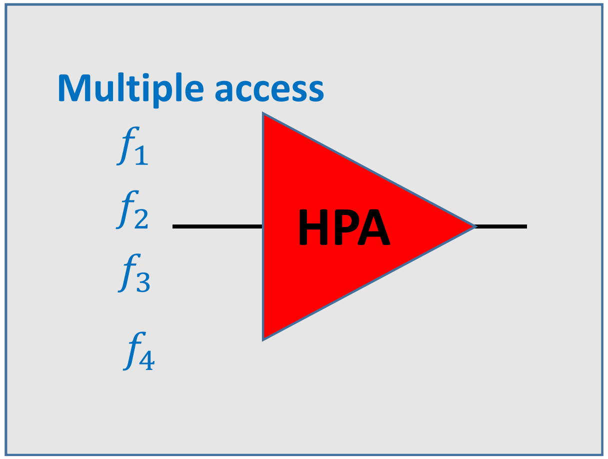
$$PAE = \frac{P_{OUT}(t) - P_{IN}(t)}{P_{DC}} = \frac{P_{OUT} - \frac{P_{OUT}}{G_P}}{P_{DC}}$$

$$PAE = \frac{P_{OUT}}{P_{DC}}\left(1 - \frac{1}{G_p}\right) = \eta\left(1 - \frac{1}{G_p}\right)$$

@ low frequency $\rightarrow (G_p \gg) \rightarrow \frac{1}{G_p} \ll \rightarrow PAE \simeq \eta$.

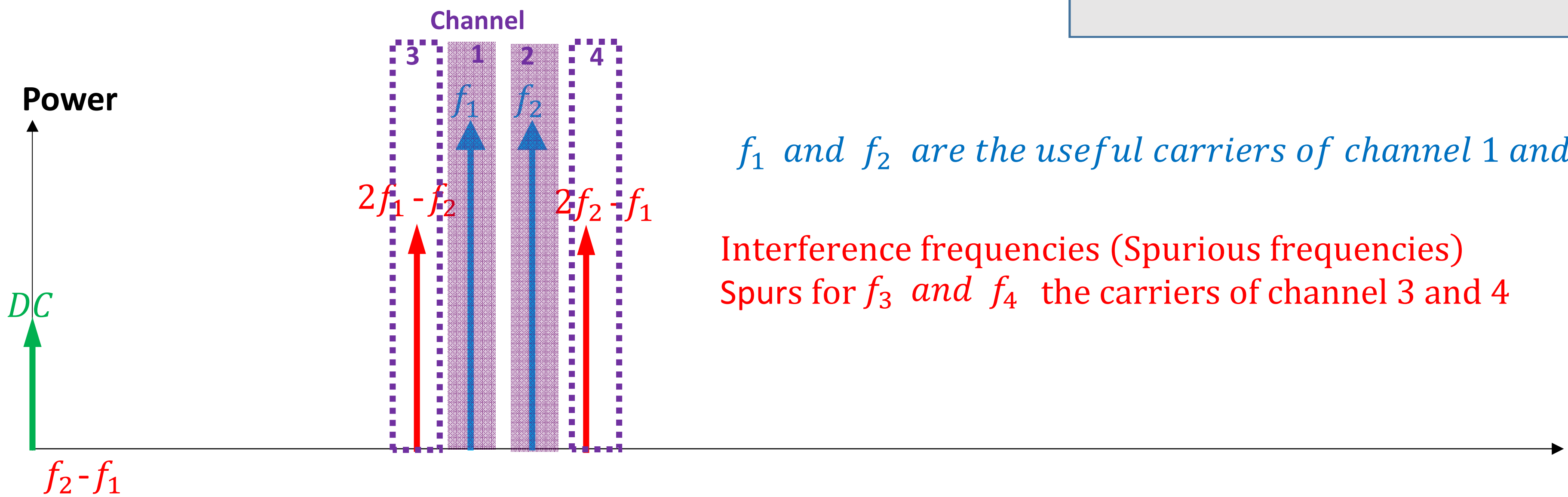
@ high frequency $\rightarrow G_p \downarrow \rightarrow PAE < \eta$

Intermodulation products for power amplifiers



Two carriers f_1 and f_2 in a 3rd order nonlinearity → **intermodulation products**

3rd order intermodulation (IM3) → Critical for multiple access



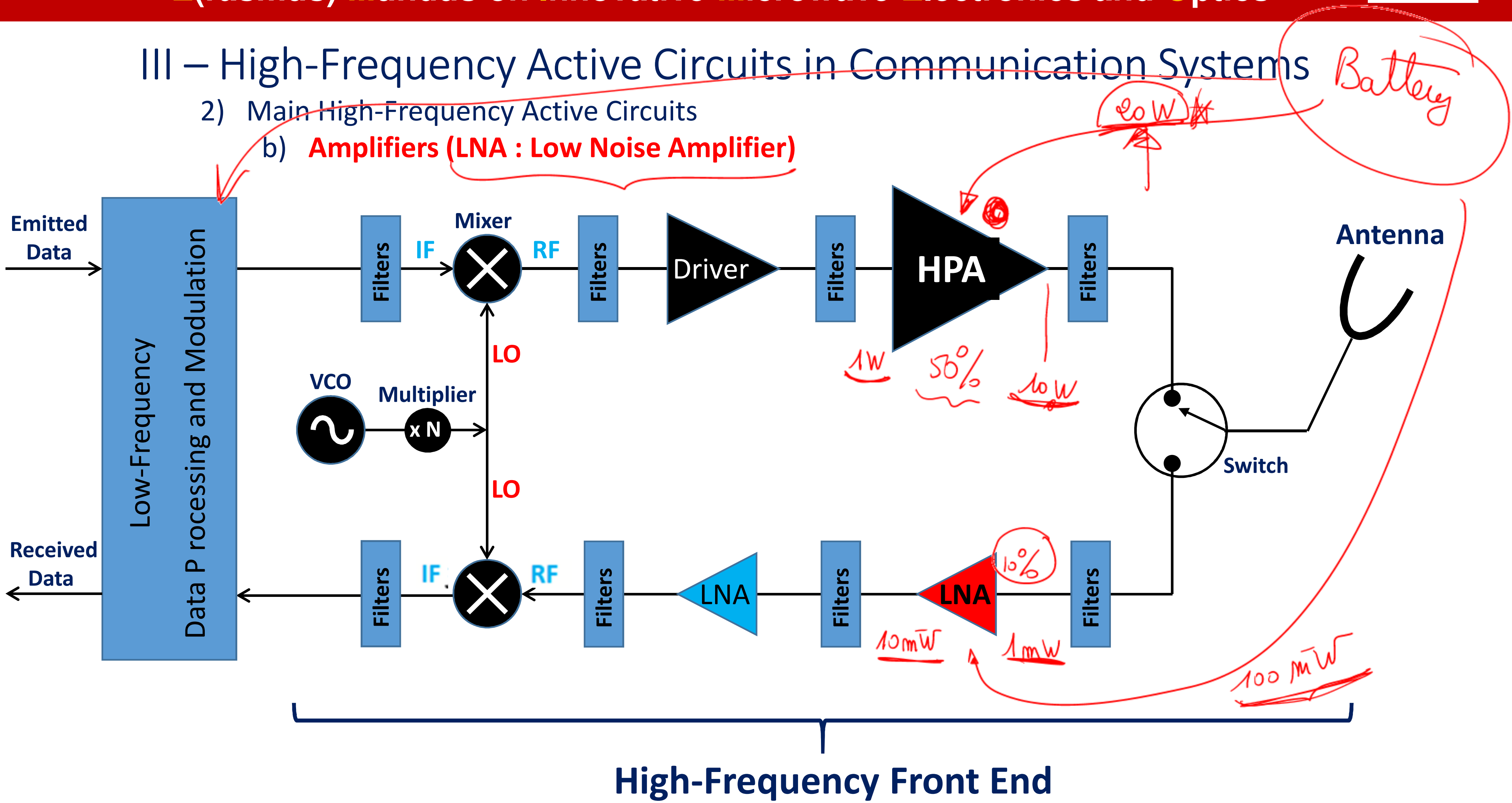
f_1 *and* f_2 *are the useful carriers of channel* 1 *and* 2

Interference frequencies (Spurious frequencies)
Spurs for f_3 *and* f_4 the carriers of channel 3 and 4

III – High-Frequency Active Circuits in Communication Systems

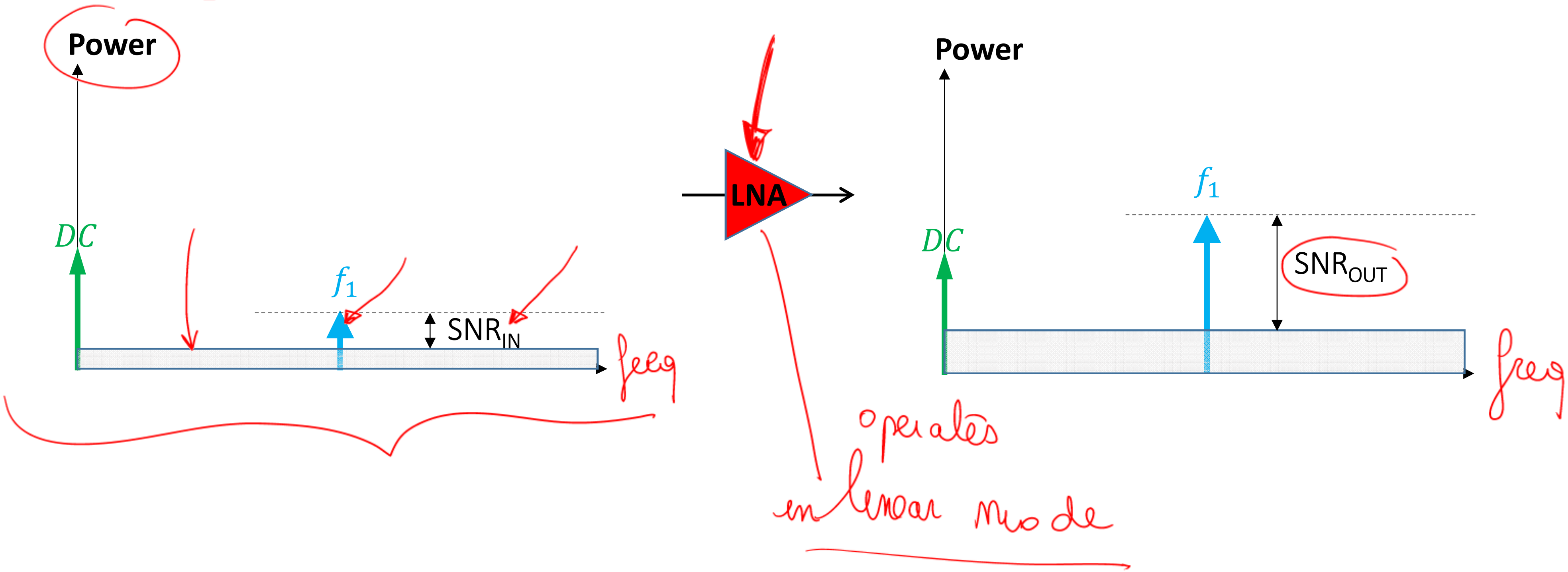
2) Main High-Frequency Active Circuits

b) Amplifiers (LNA : Low Noise Amplifier)



LNA (Low Noise Amplifiers)

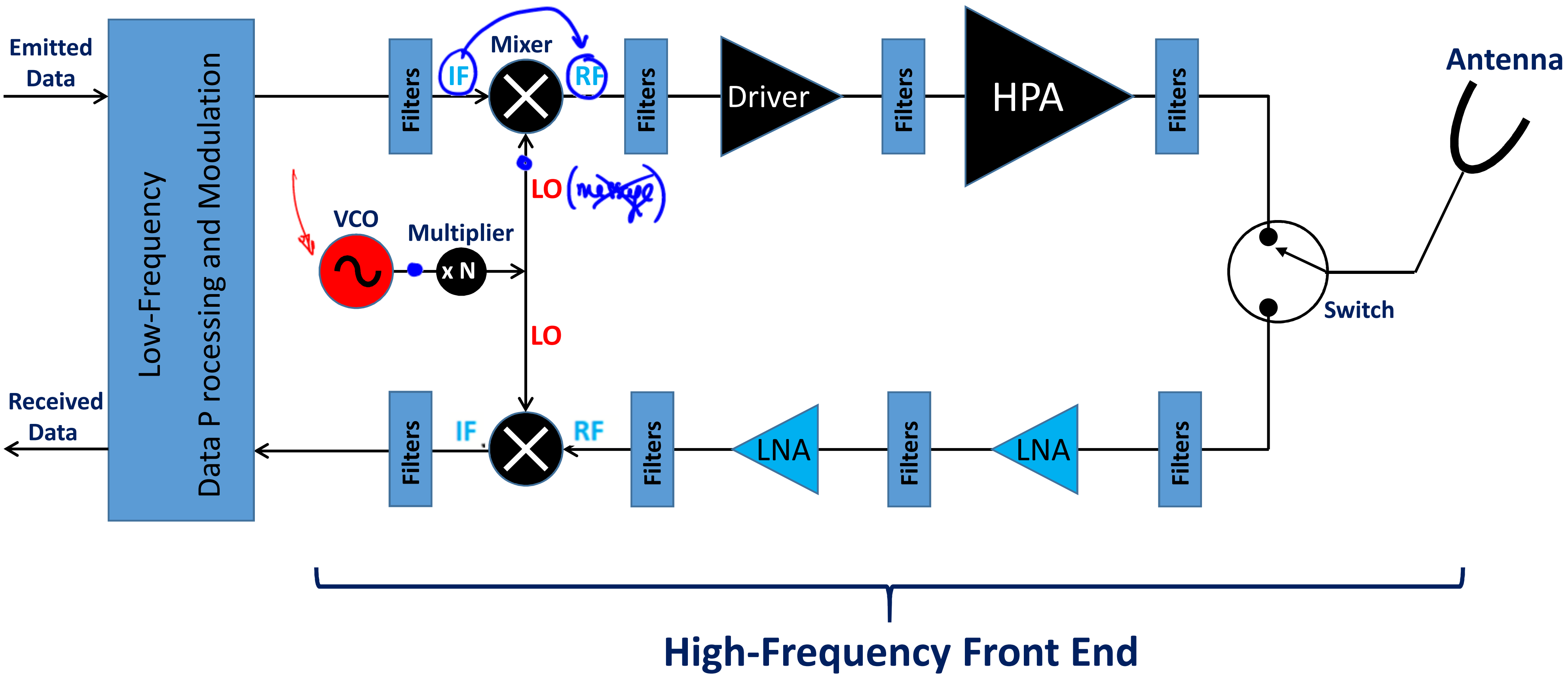
- Optimisation of Signal to Noise Ratio for LNAs → Noise property of LNA (Noise Factor)
- Increase the Signal to Noise Ratio (SNR)
- Linear operation due to the reception of very weak signals which have to be greater than the noise floor



III – High-Frequency Active Circuits in Communication Systems

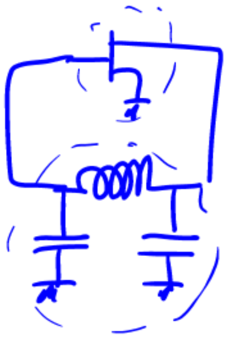
2) Main High-Frequency Active Circuits

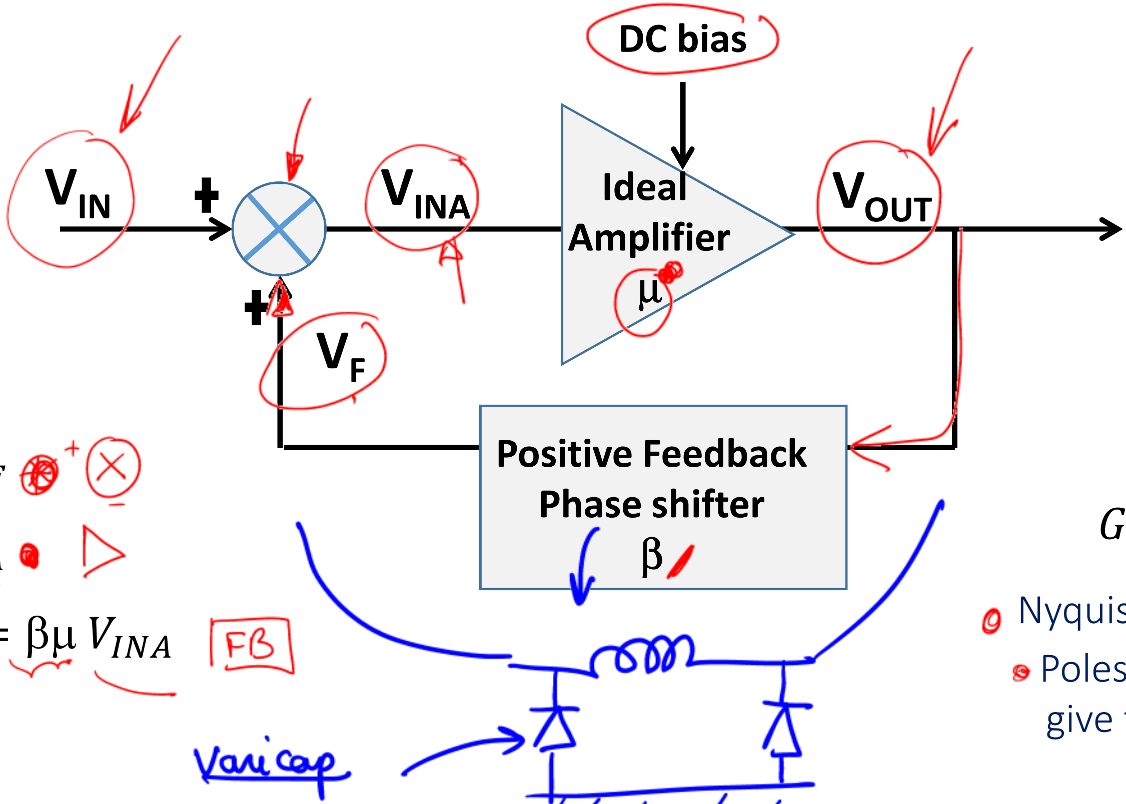
c) Oscillators (LO : Local Oscillator) (VCO: Voltage Controlled Oscillator)



Block diagram of a feedback oscillator (Signal reference)

- Oscillations come from the control of the unstability for an amplifier(Gain → ∞) at a given frequency
- Optimisation of Oscillator's noise → Thermal noise, 1/f noise …
- Critical to ensure a perfect up-conversion (emission) and down-conversion (reception)
- Nonlinear operation (the oscillation frequency comes from the selective amplification of the noise)





$$V_{INA} = V_{IN} + V_F$$

$$V_{OUT} = \mu\, V_{INA}$$

$$V_F = \beta\, V_{OUT} = \beta\mu\, V_{INA}$$

FB

Closed-loop transfer function

$$Gain = \frac{V_{OUT}}{V_{IN}} = \frac{\mu\, V_{INA}}{V_{INA} - V_F}$$

$$Gain = \frac{V_{OUT}}{V_{IN}} = \frac{\mu\, V_{INA}}{V_{INA} - \beta\mu\, V_{INA}}$$

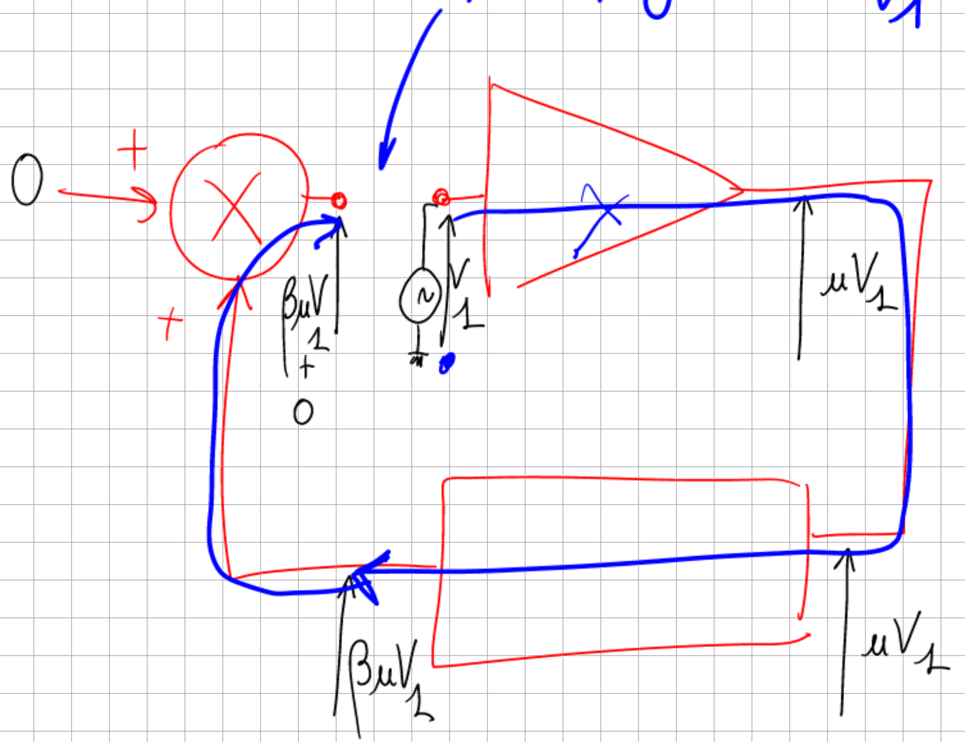
$$Gain(\ ) = \frac{V_{OUT}}{V_{IN}} = \frac{\mu(\omega)}{1 - \beta(\omega)\mu(\omega)}$$

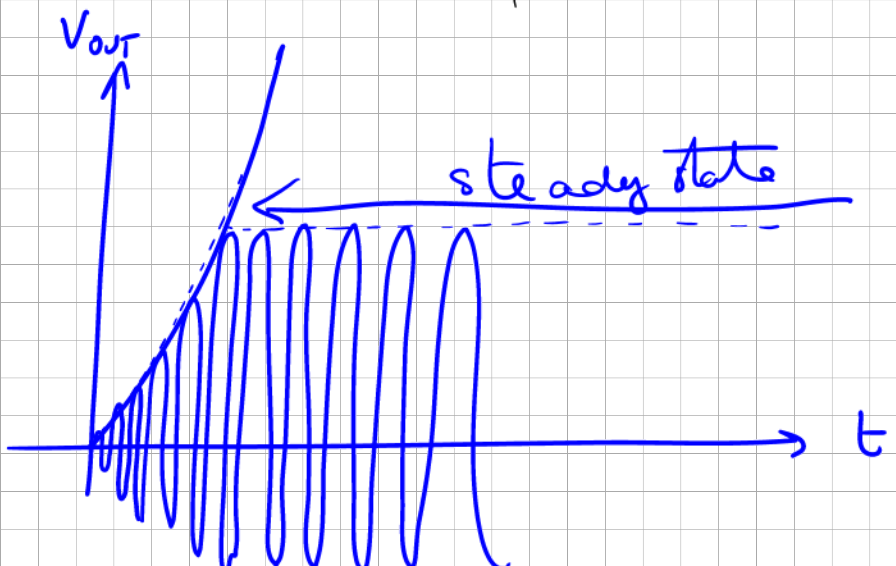
- Nyquist Criterion:
  - Poles of the transfer function = Roots of (1-βμ) give the oscillation frequencies

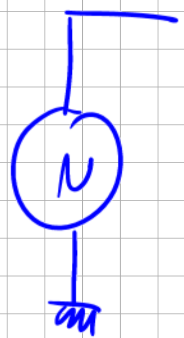
In the case (V_{IN}=0), Barkhausen's criterions are on the loop gain : Modulus $|\beta\mu|_{@\omega_{osc}} \geq 1$ and $\arg(\beta\mu)_{@\omega_{osc}} = 2\pi n$

open loop gain $= \frac{\beta \mu V_1}{V_1} = \beta\mu$

$$G = \frac{\mu}{1-\beta\mu}$$







Issue of 1/F noise of oscillators for ideal mixer operation

- Oscillations come from the control of the unstability for an amplifier(Gain → ∞) at a given frequency
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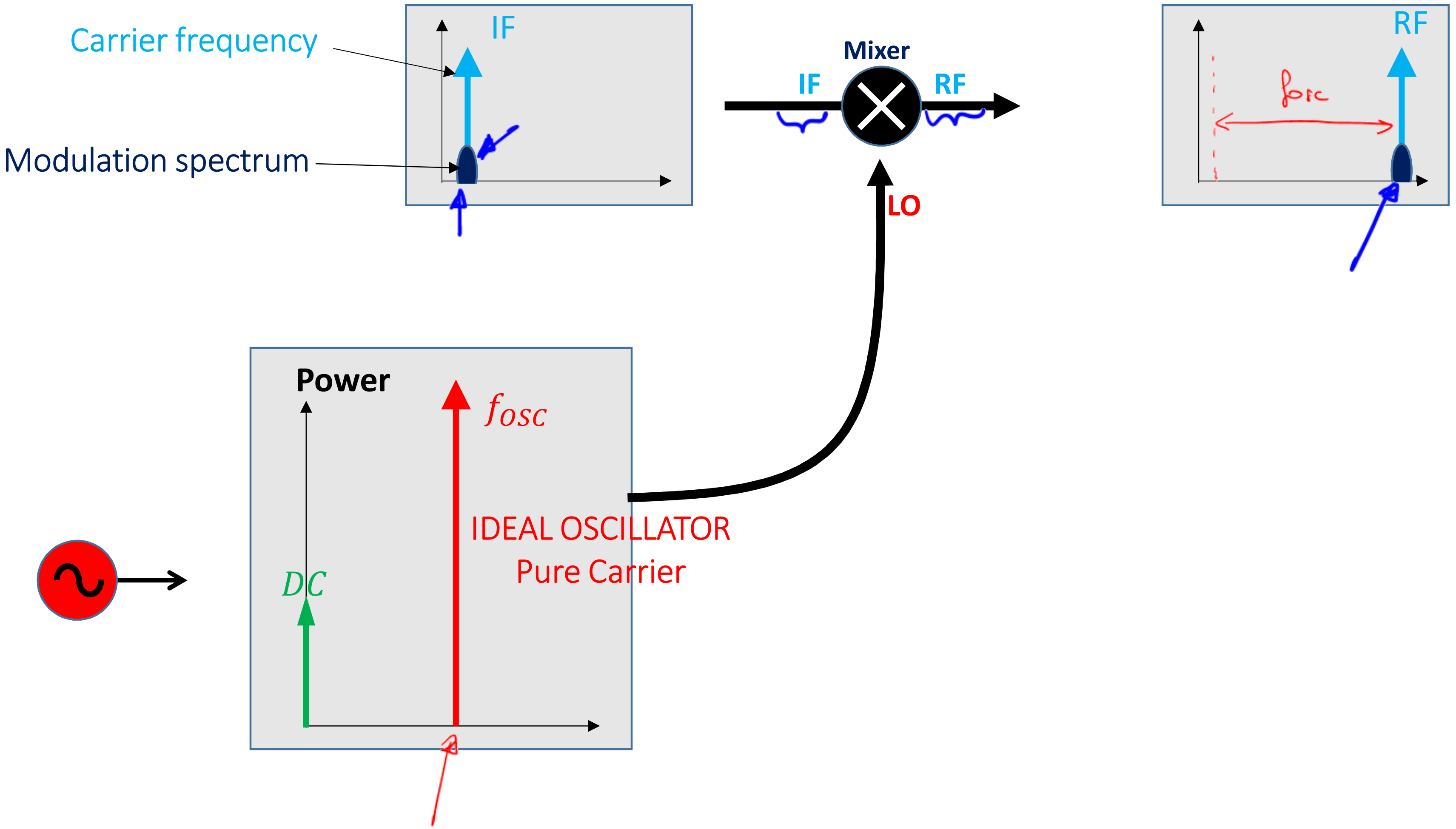
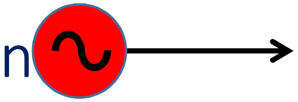


Issue of 1/F noise of oscillators for ideal mixer operation



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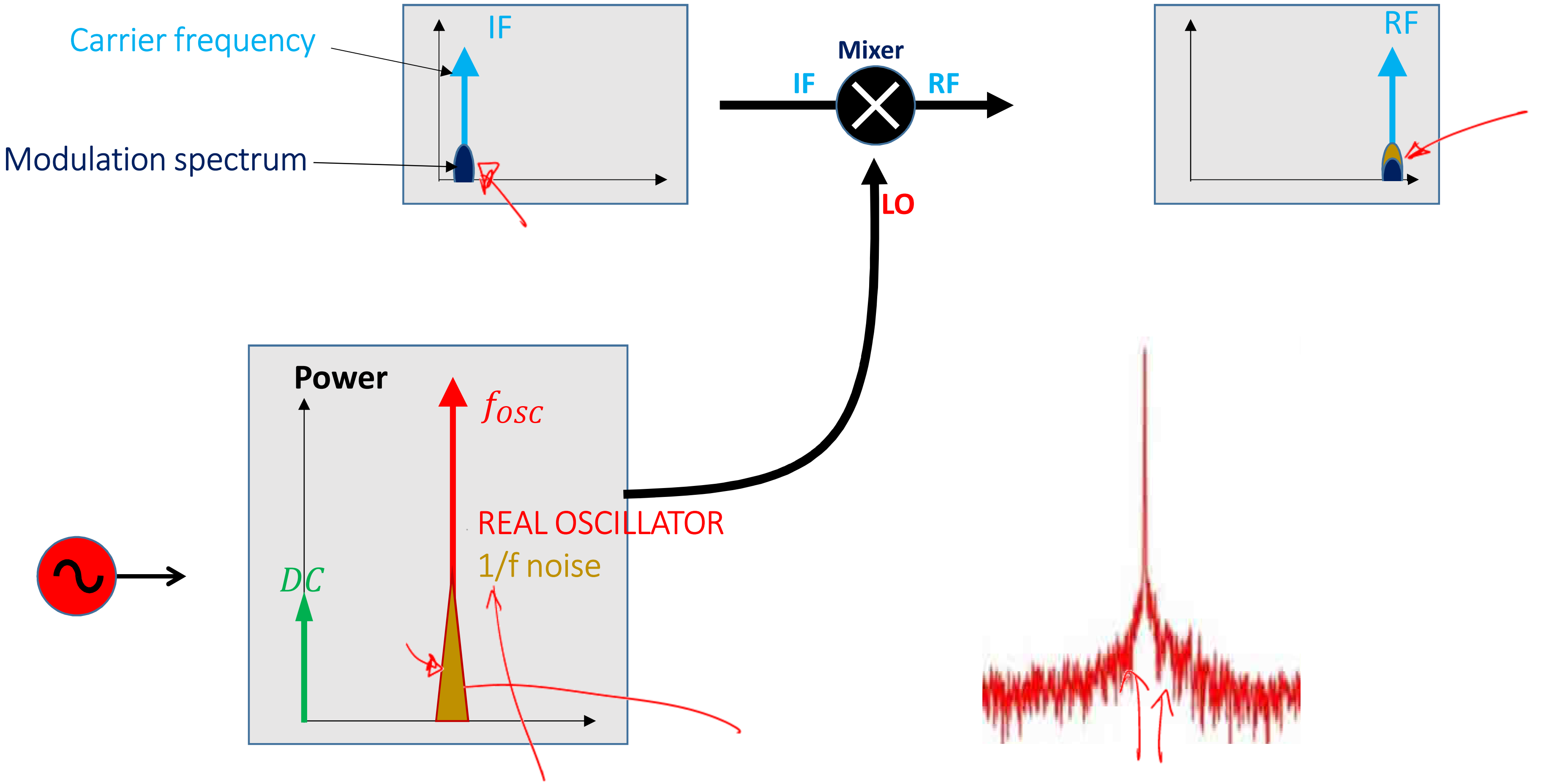
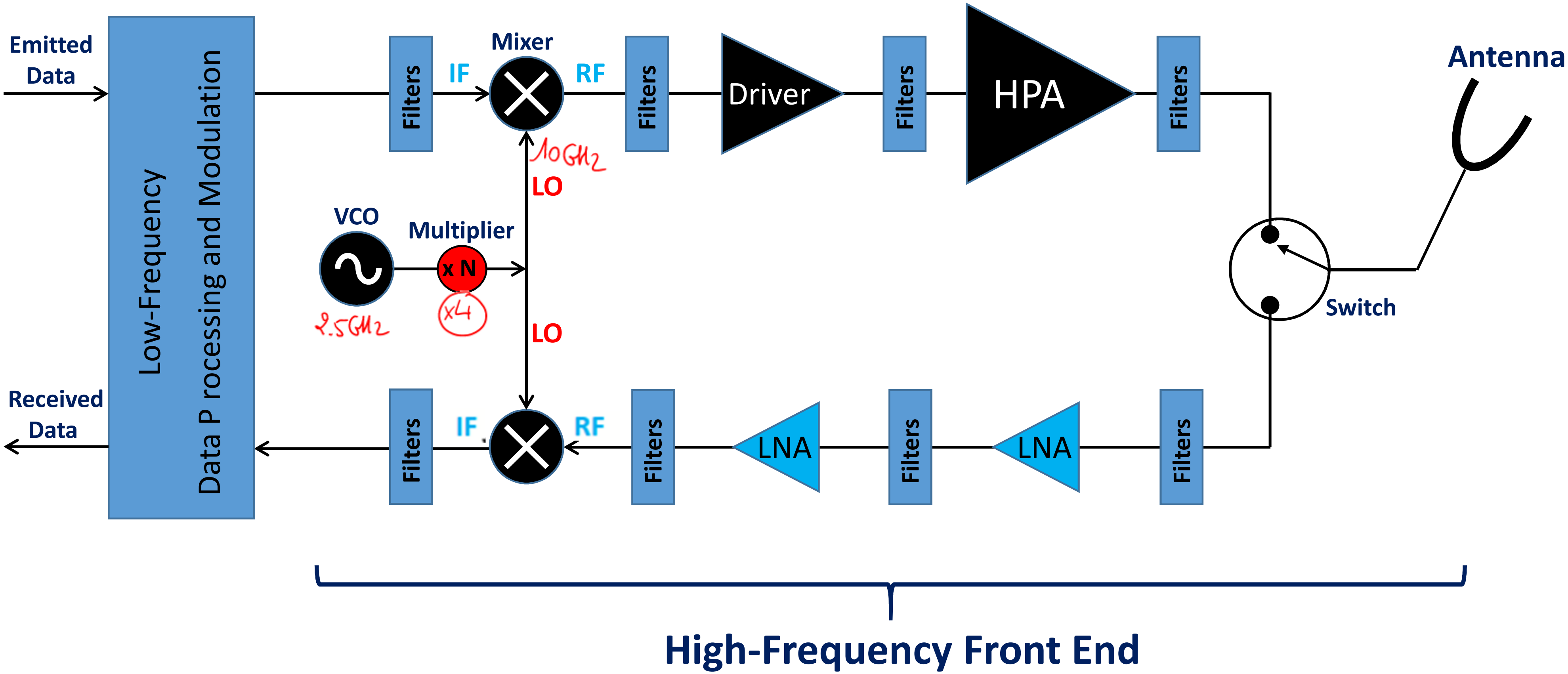


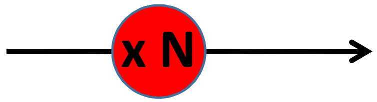
III – High-Frequency Active Circuits in Communication Systems

2) Main High-Frequency Active Circuits

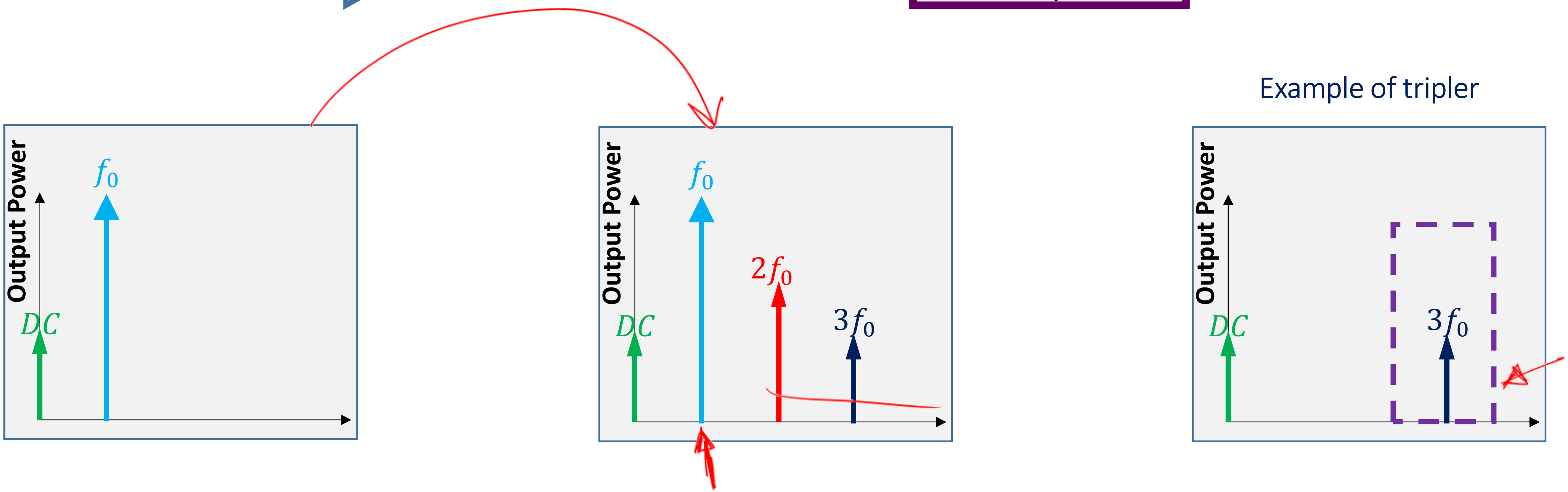
d) Multipliers

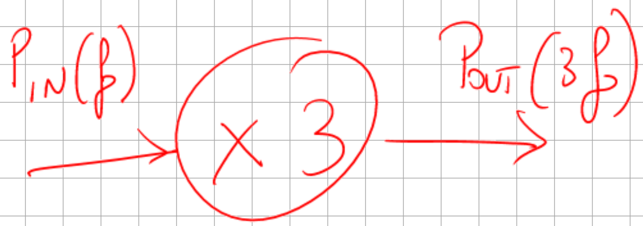


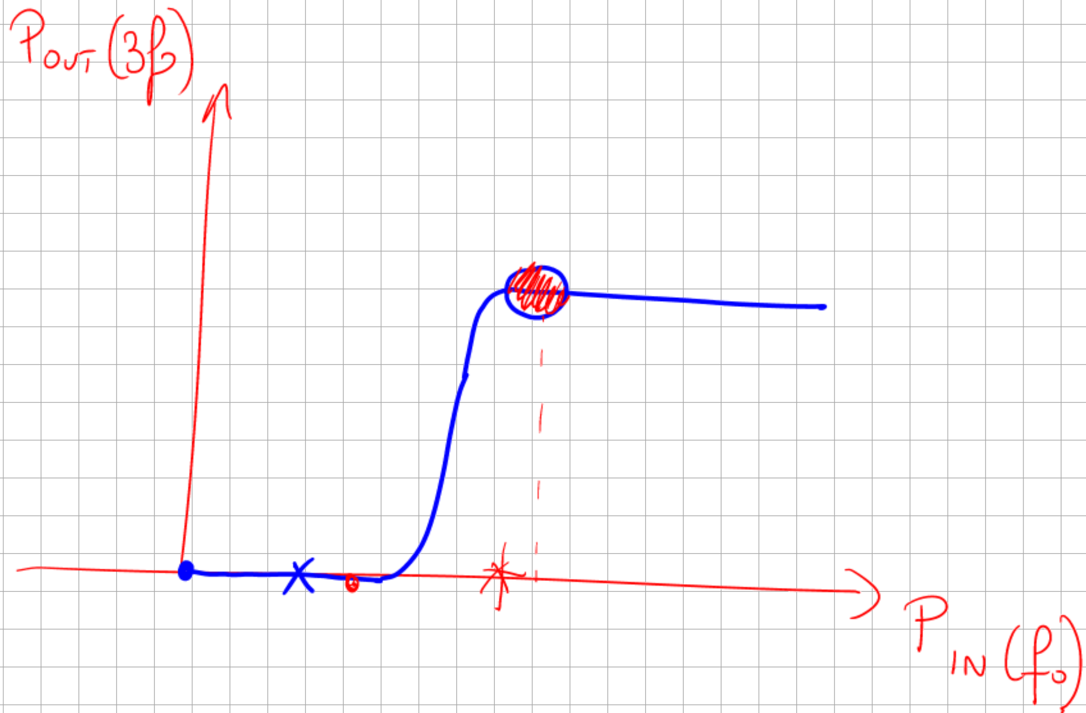
Block diagram of a frequency multiplier

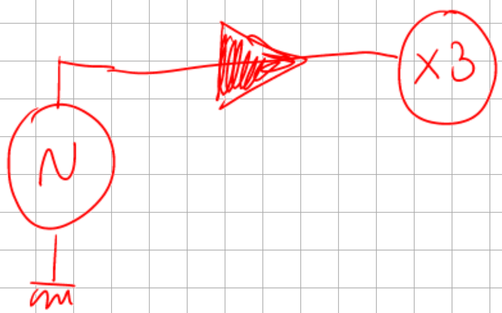


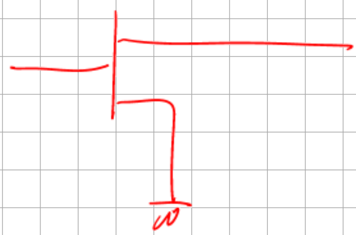
- Generate harmonics by using an amplifier in its nonlinear regime
- Select by band-pass filter the required output harmonic

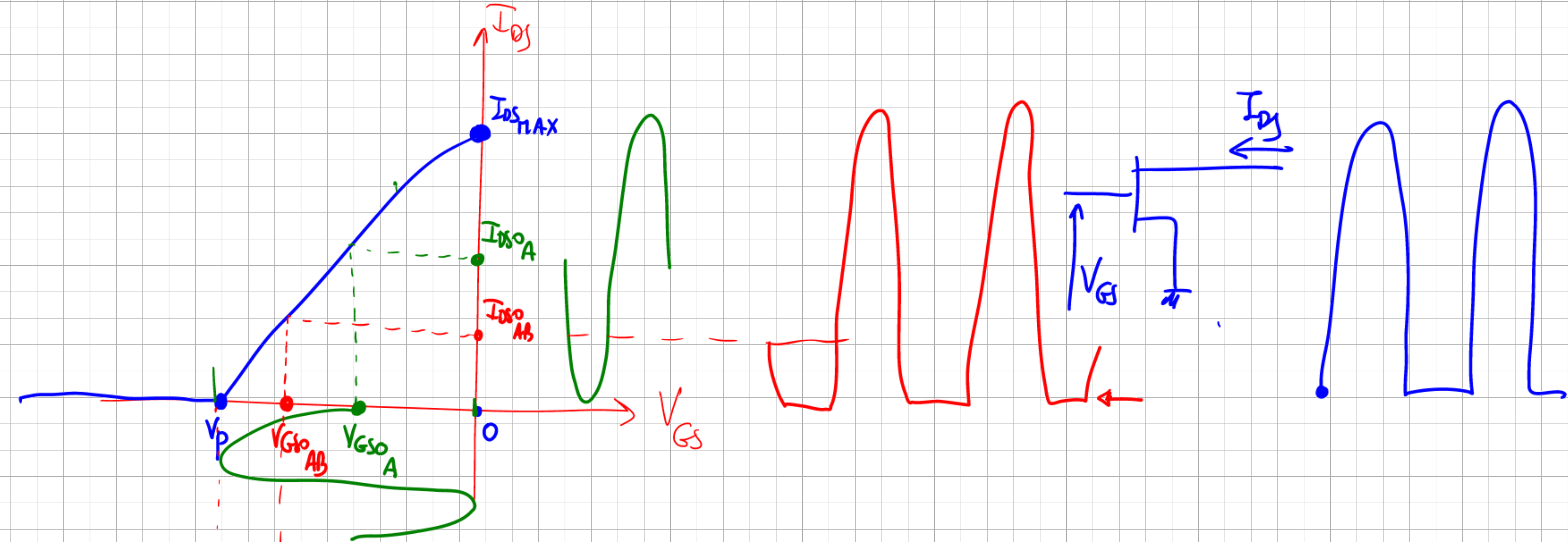


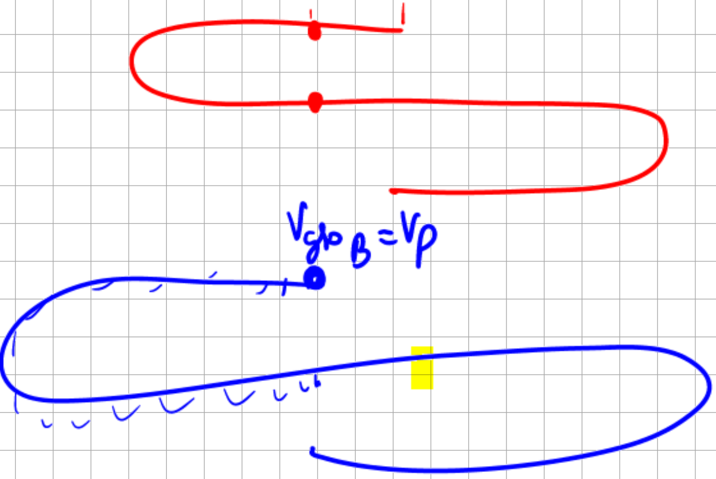

$P_{IN}(f)$
$\times 3$
$P_{OUT}(3f)$


$P_{OUT}(3f)$
$P_{IN}(f_0)$


$\times 3$







operating classes

A class → $\eta \leq 50\%$

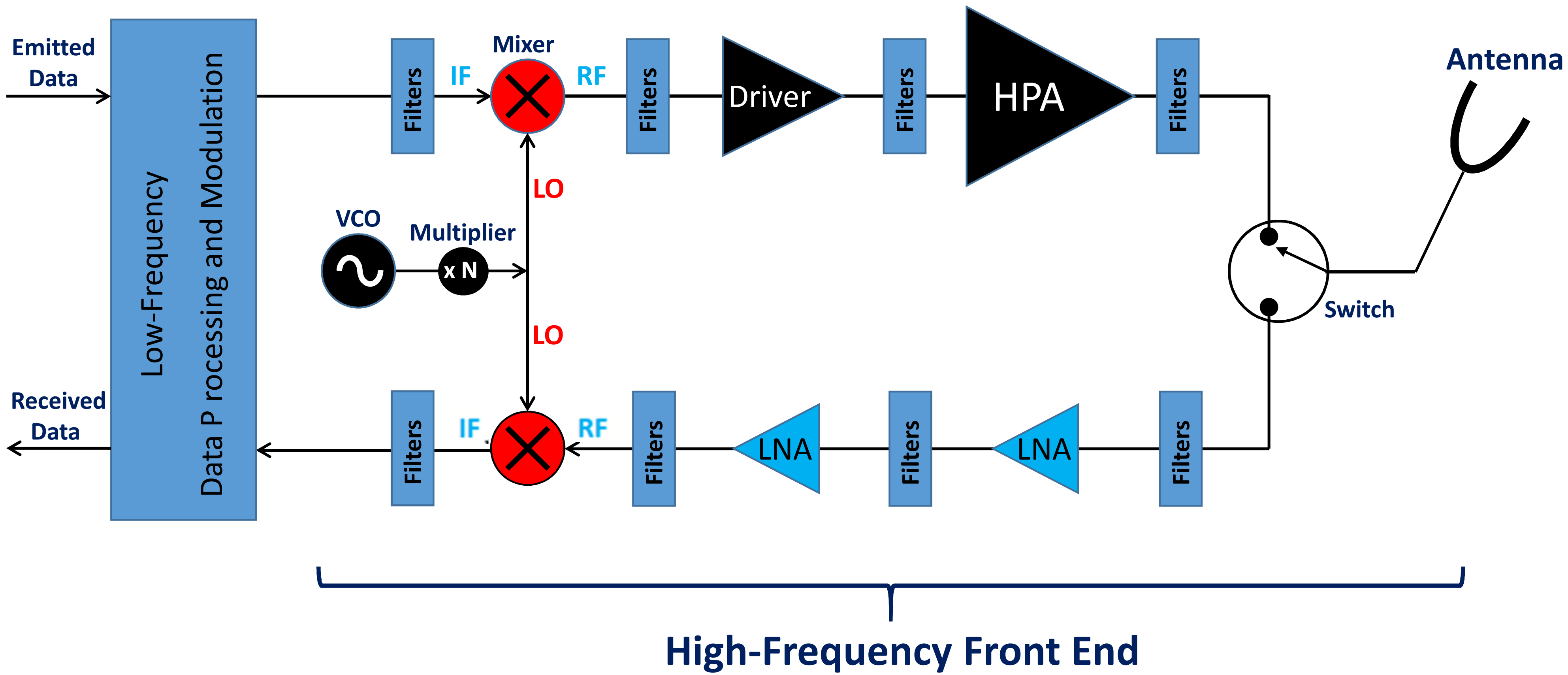
AB class → $\eta \nearrow$

B class → $\eta \nearrow\nearrow$

III – High-Frequency Active Circuits in Communication Systems

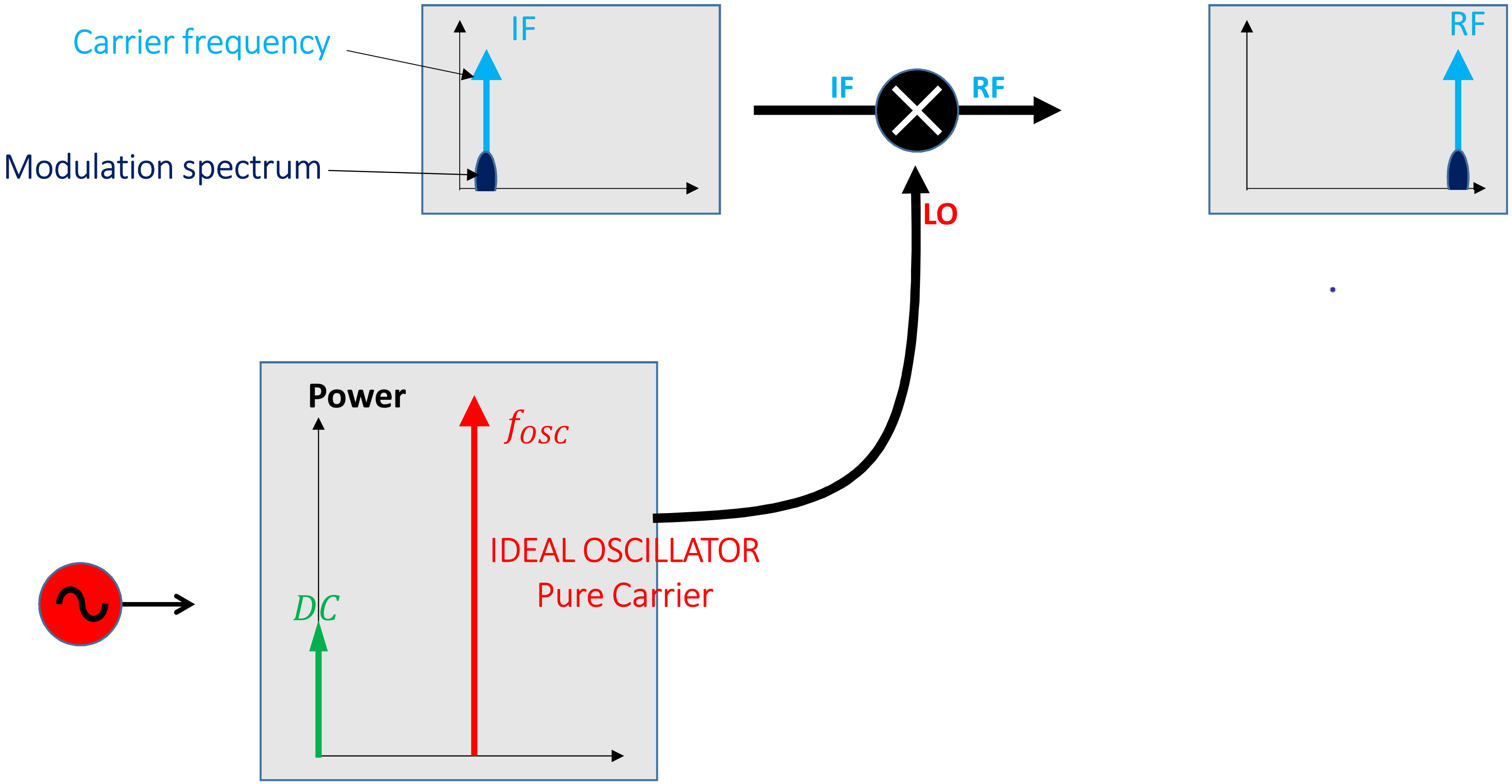
2) Main High-Frequency Active Circuits

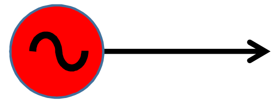
e) Mixers (Up-converter and Down-converter)



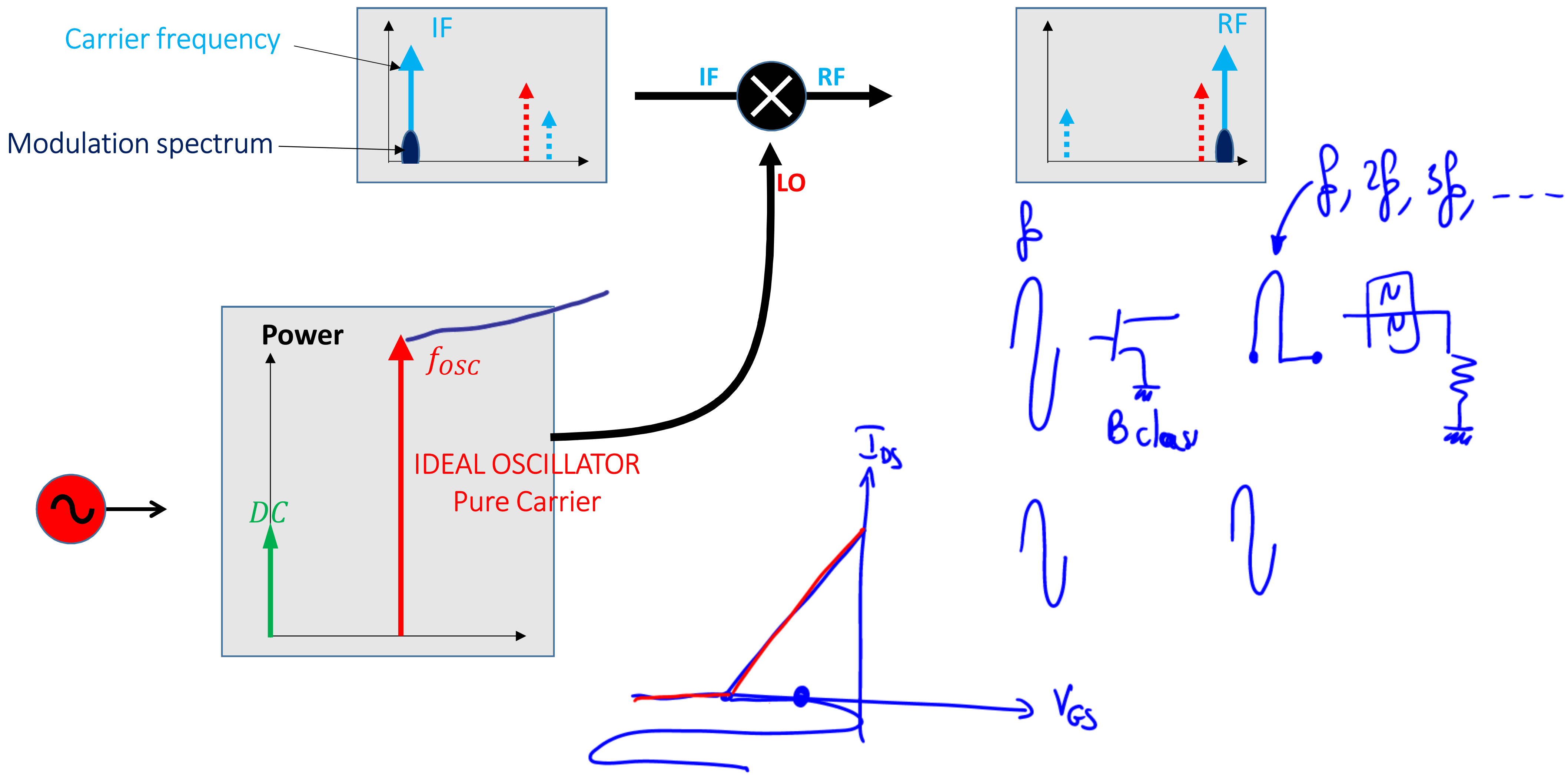
Issues of mixer designs (Conversion gain, Isolations...)

Ideal Mixer



Issues of mixer designs (Conversion gain, Isolations…) 

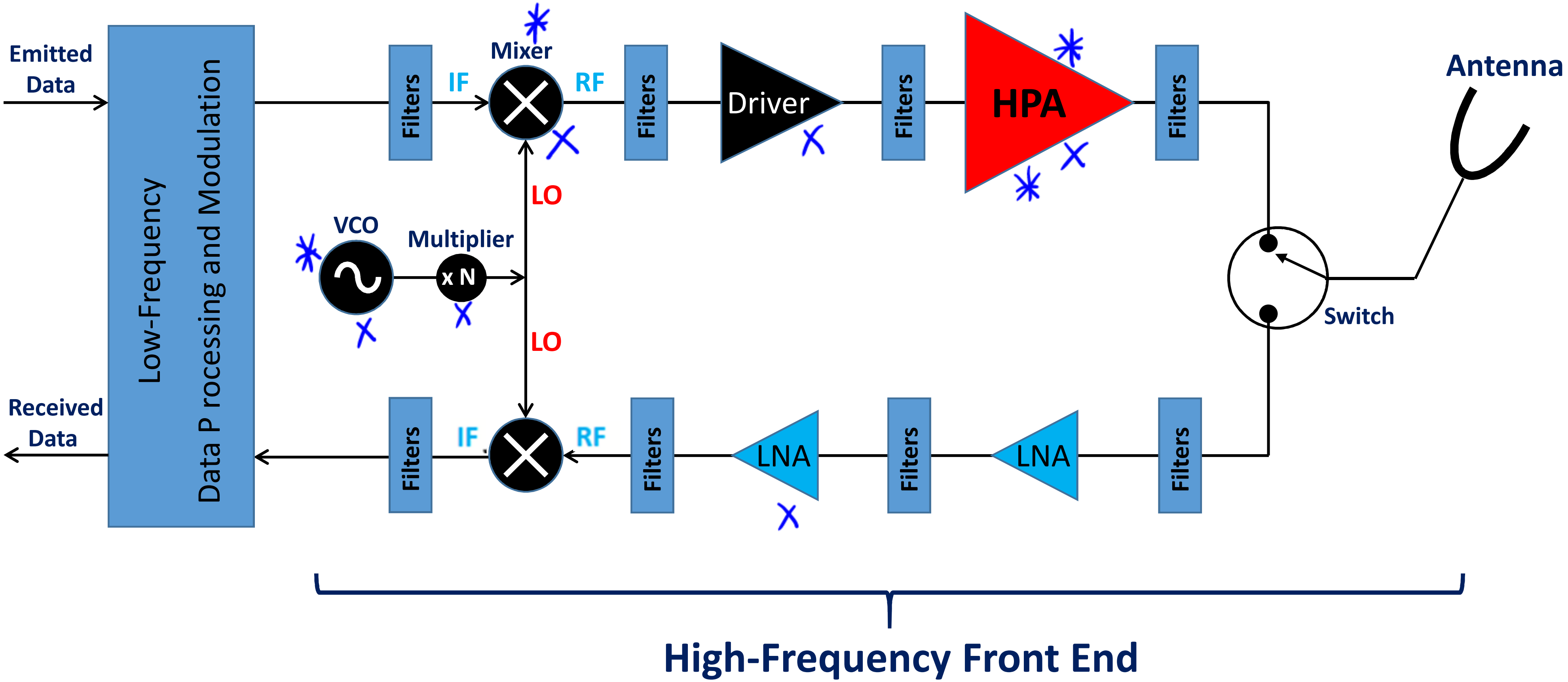
Real Mixer



III – High-Frequency Active Circuits in Communication Systems

2) Main High-Frequency Active Circuits

f) HPA (Tradeoffs Linearity vs PAE & Power → New Architectures → Master 2 & Research



III – High-Frequency Active Circuits in Communication Systems

2) Main High-Frequency Active Circuits

f) HPA (Tradeoffs Linearity vs PAE & Power → New Architectures → Master 2 & Research

HPA

DARPA
(Defense Advanced Research Project Agency)

new war systems

CNES

ESA

DGA

EDA

European Defense Agency

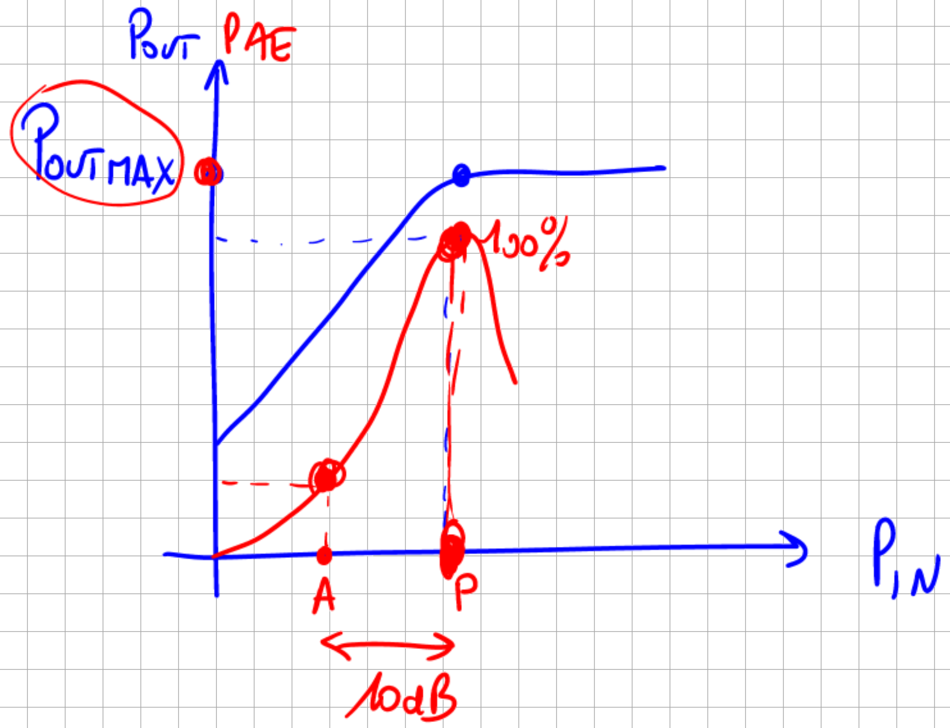
European Space Agency

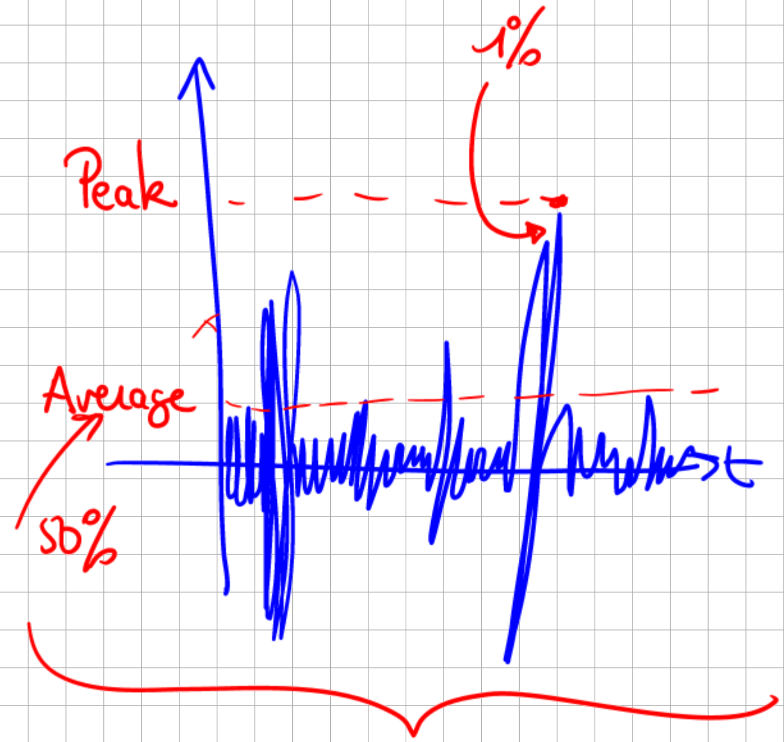
TAS (

Thalès

* ET (Envelope Tracking)
* DOHERTY
* LINC (Linear amplification with Nonlinear Components)

GSM





PAPR (Peak to Average Power Ratio) ⟷ characterize a modulated signal

dB

10dB PAPR

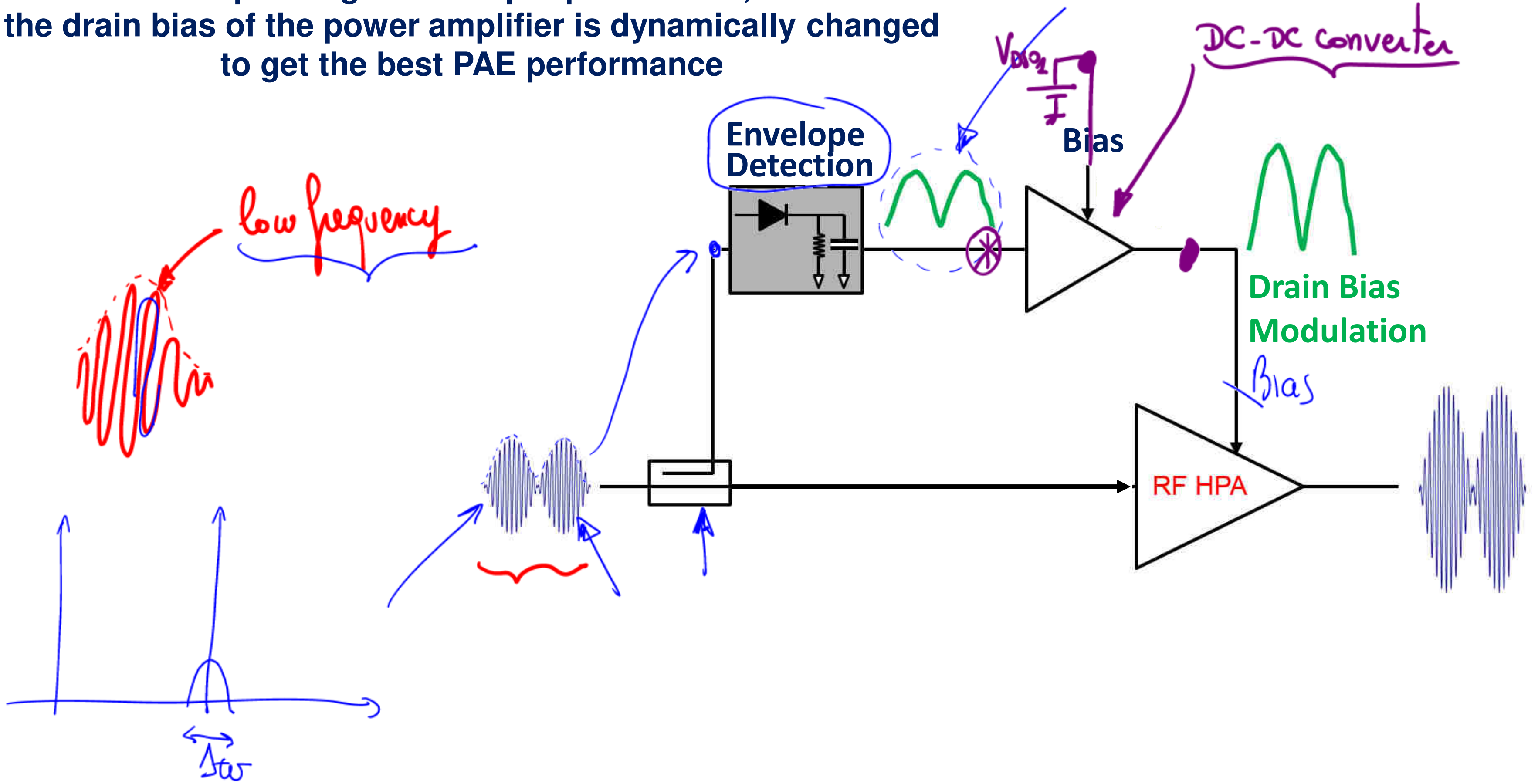
III – High-Frequency Active Circuits in Communication Systems

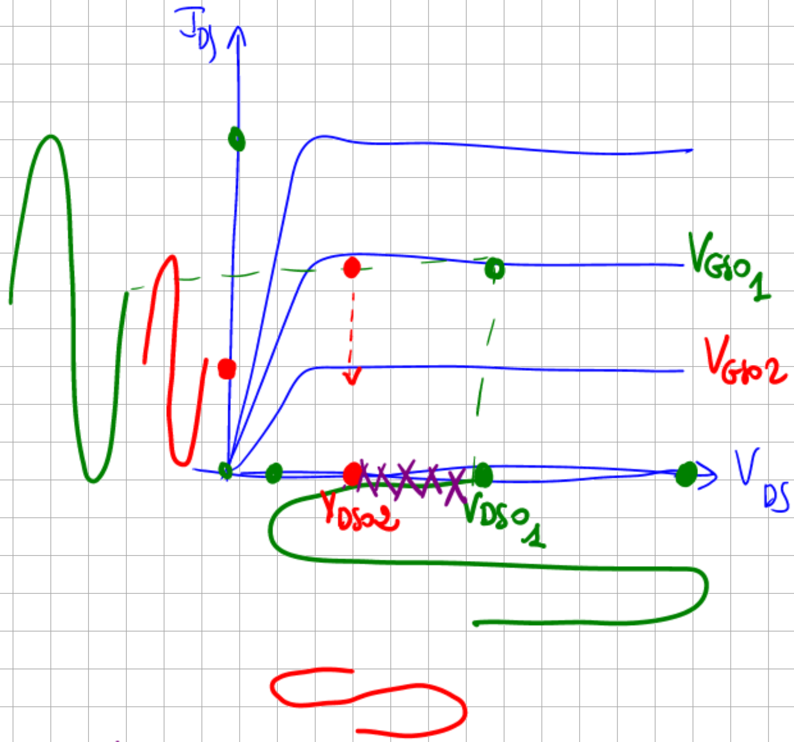
2) Main High-Frequency Active Circuits

f) **HPA (Tradeoffs Linearity vs PAE & Power → New Architectures → Master 2 & Research**

- ET (Envelope Tracking) *

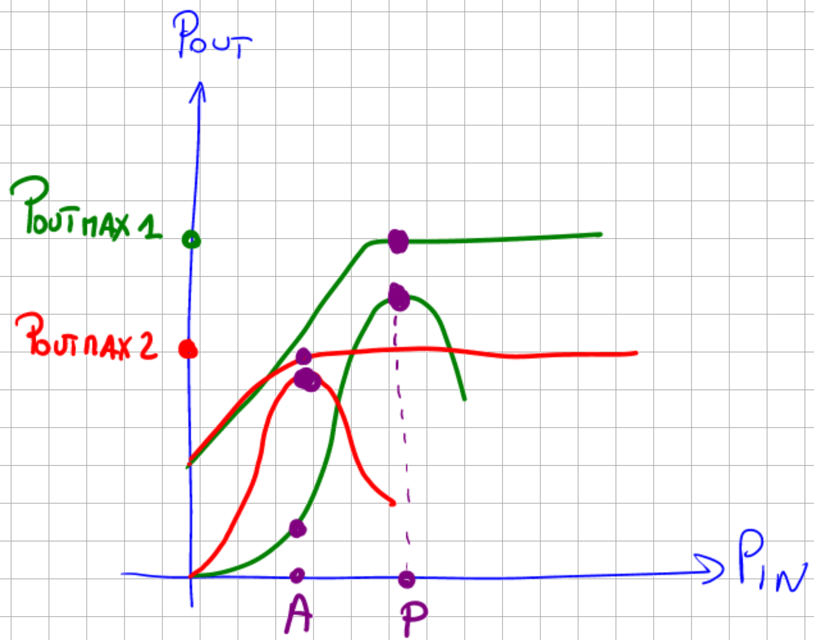
Depending on the input power level,
the drain bias of the power amplifier is dynamically changed
to get the best PAE performance





I_{DS}
V_{GS0_1}
V_{GS0_2}
V_{DS}
V_{DS0_2}
V_{DS0_1}

$P_{OUT_{MAX1}}$



P_{OUT}
$P_{OUT\,MAX\,1}$
$P_{OUT\,MAX\,2}$
P_{IN}
A
P

2

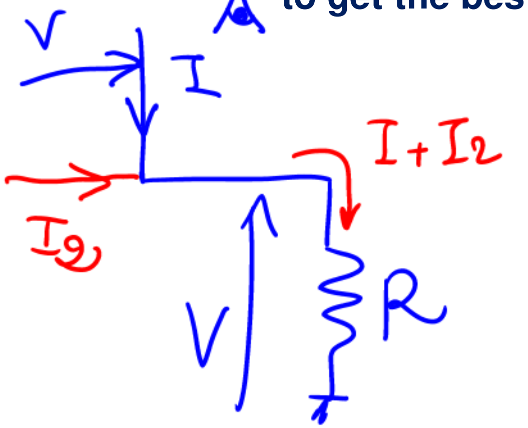
III – High-Frequency Active Circuits in Communication Systems

2) Main High-Frequency Active Circuits

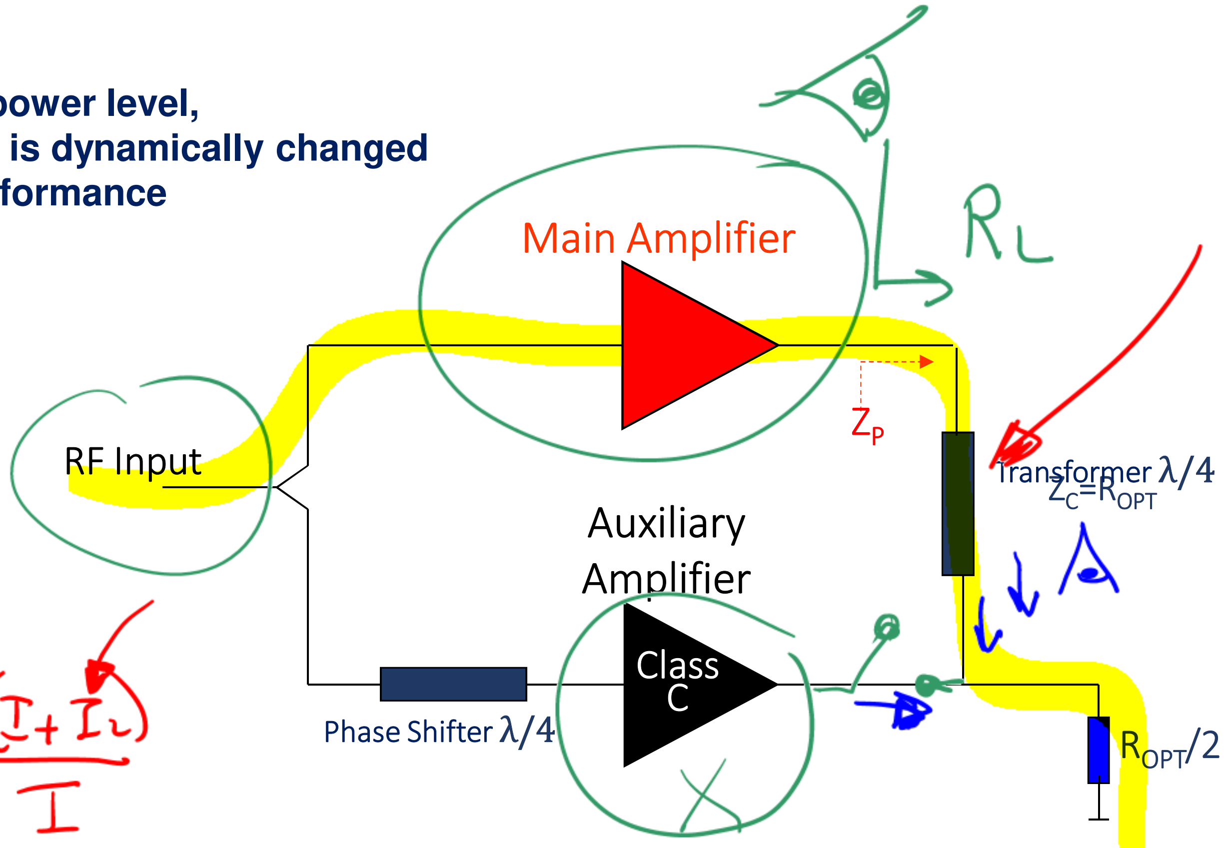
f) HPA (Tradeoffs Linearity vs PAE & Power → New Architectures → Master 2 & Research

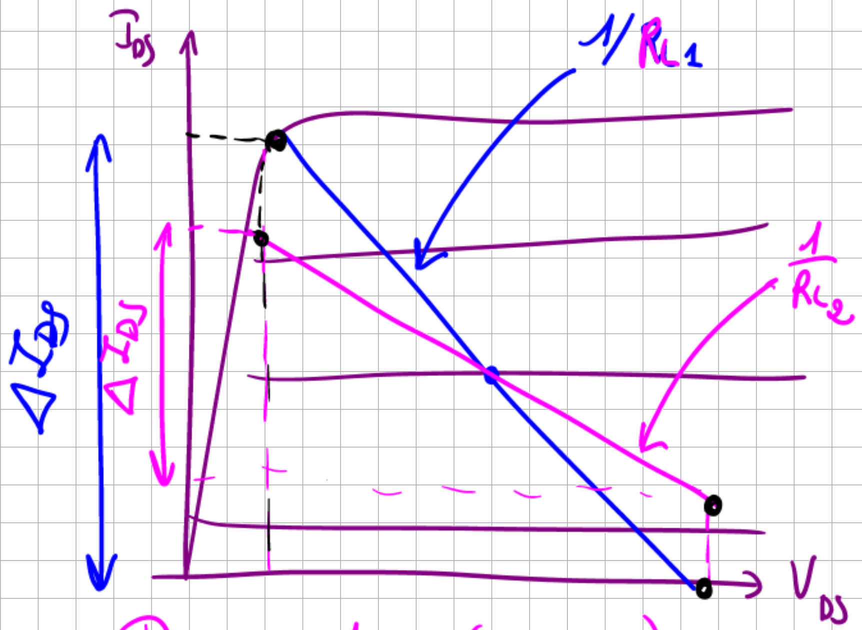
- DOHERTY

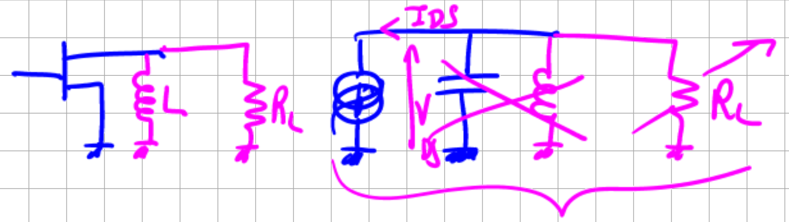
Depending on the input power level, the load Z_P seen by the main amplifier is dynamically changed to get the best PAE performance



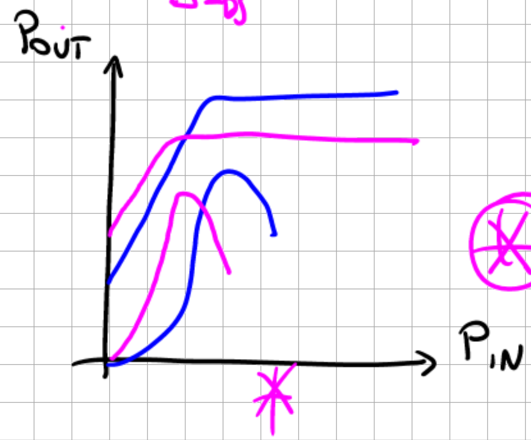
$$R_L = \frac{V}{I} = \frac{R(I+I_2)}{I}$$







$$R_L = \frac{\Delta V_{DS}}{\Delta I_{DS}}$$



$$P_{OUT} \simeq \frac{1}{2} \mathrm{Re}\left(V_{OUT} I_{OUT}^{*}\right)$$

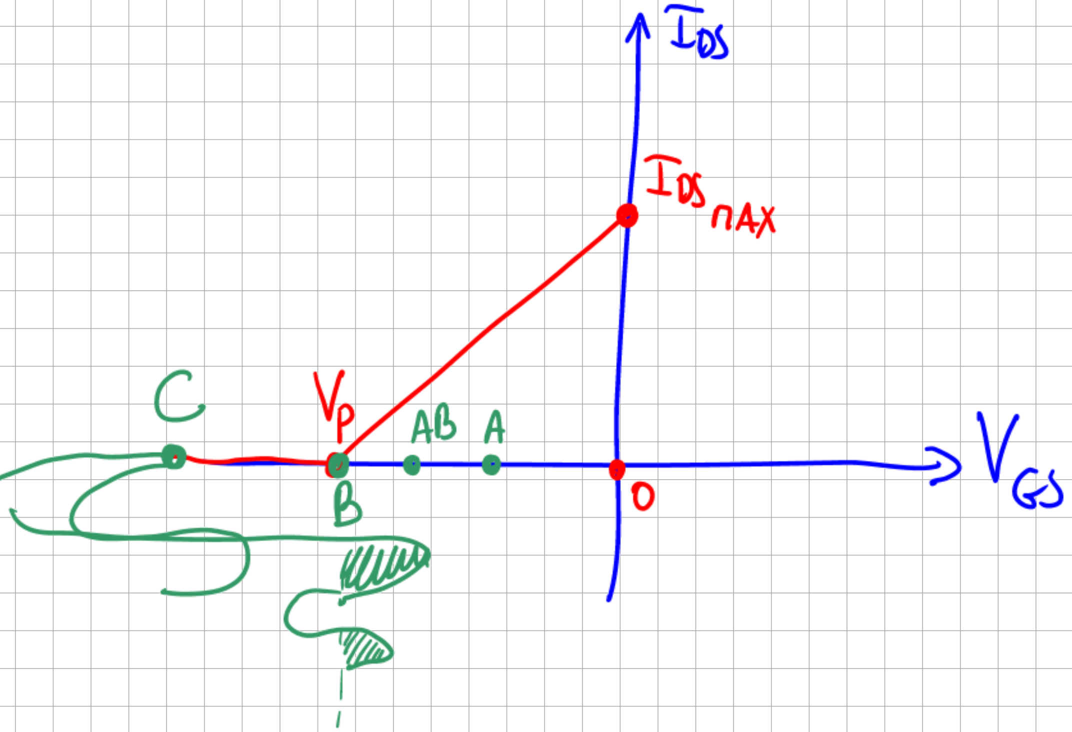
$$= \frac{1}{2} \mathrm{Re}\left(R_L \left|I_{OUT}\right|^2\right)$$

$$= \frac{1}{2} R_L \left|I_{OUT}\right|^2$$

$$= \frac{1}{8} \left(V_{DS_{MAX}} - V_{DS_{MIN}}\right)\left(I_{DS_{MAX}} - I_{DS_{MIN}}\right)$$

X

C class operation



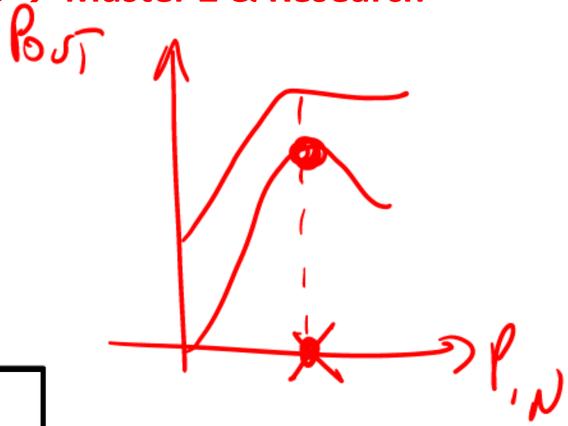
IDS
IDS MAX
VGS
VP
C
AB
A
B
0

III – High-Frequency Active Circuits in Communication Systems

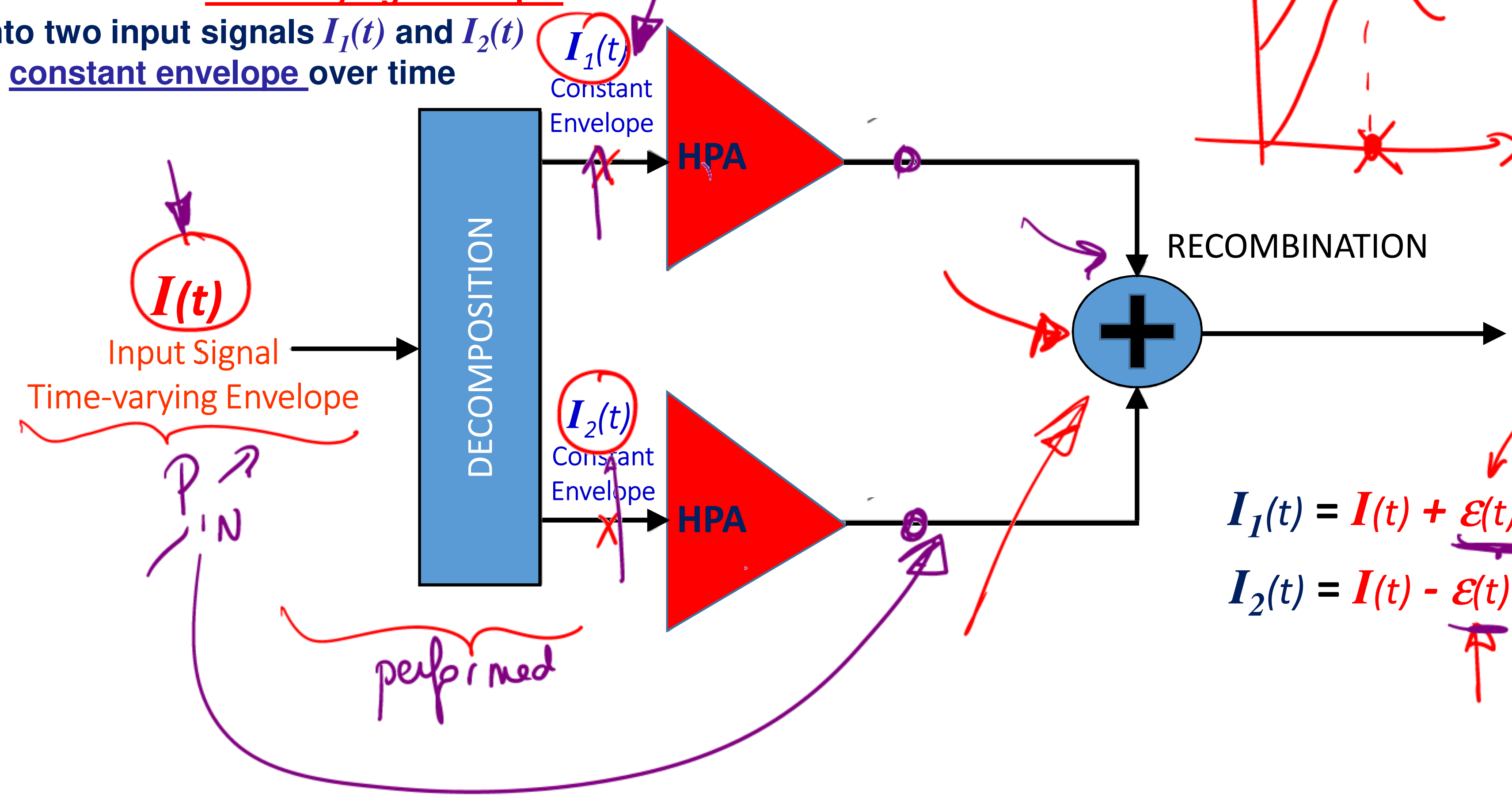
2) Main High-Frequency Active Circuits

f) **HPA (Tradeoffs Linearity vs PAE & Power → New Architectures → Master 2 & Research**

LINC (Linear amplification with Nonlinear Components)

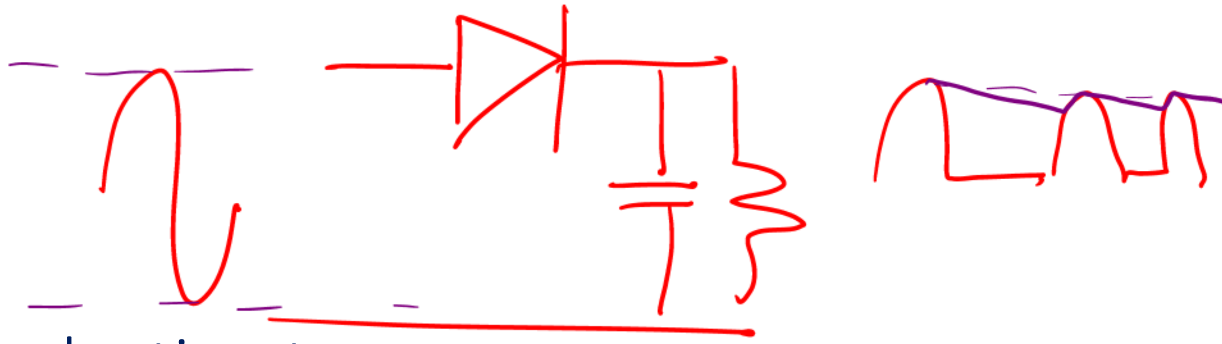


The input signal *I(t)* which has a time-varying envelope is decomposed into two input signals $I_1(t)$ and $I_2(t)$ which have a constant envelope over time



$I_1(t) = I(t) + \varepsilon(t)$

$I_2(t) = I(t) - \varepsilon(t)$



Introduction to

Nonlinear Modeling Techniques

of Microwave Transistors

Design Methods

of Narrow-band Power Amplifiers

Architectures

of High-Frequency Mixers

Architectures

of Wideband Resistive and Distributed Power Amplifiers

Architectures

of Nonlinear Active Circuits

controlled by Cold FETs

a) Power Losses / Gain / Bias / Efficiency / Temperature

Electrothermal Analogy

Thermal Variable	Electrical Equivalent
Temperature (K)	Potential (V)
Temperature difference (K) $\theta = T - T_0$	Voltage (V)
Thermal flux = Dissipated Power (W)	Current (A)
Thermal Resistance (convection) (K/W)	Resistance R_{TH} (Ω)
Thermal Capacitance (J/W)	Capacitance C_{TH} (F)
→Thermal time constant	→Time Constant (s) $\tau_{TH} = R_{TH}.C_{TH}$

Electrothermal Analogy (simplest thermal cell)