# Basics of Active and Nonlinear High-Frequency Electronics


Copyright notice : This material can be freely used within the E.M.I.M.E.O. Erasmus Mundus consortium. Explicit authorisation of the authors is required for its use outside this E.M.I.M.E.O. consortium. This learning Programme has been funded with support from the European Commission. This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

# 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

Erasmus+

**EMIMEO**

**E(rasmus) Mundus on Innovative Microwave Electronics and Optics**

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 wideband resistive and distributed power amplifiers *(depending on the course progress)*
- Chapter VI : Architectures of non-linear active circuits controlled by cold HEMTs

# Chapter I :

## Introduction to

## active high-frequency circuits in communications systems

# I - Differences Active/Passive & Linear/Nonlinear

1) Power Losses / Gain / Bias

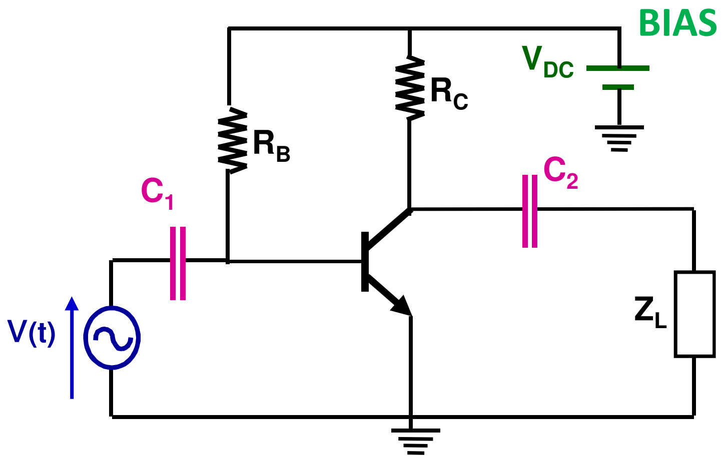
2) Linearity / Non-linearity

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

# 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, …)




Physics +

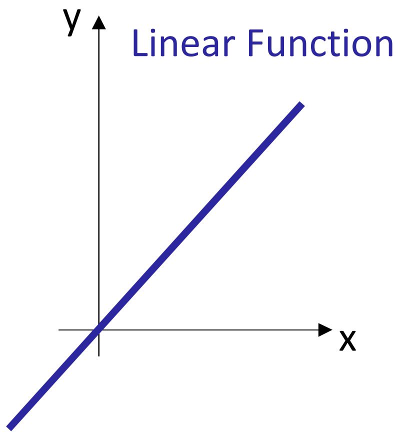
FET (Field Effect Transistor)
HEMT (High Electron Mobility Transistors)

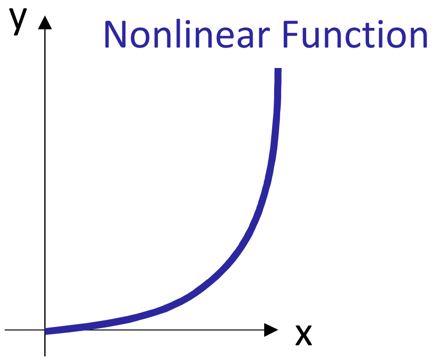
Gate
Drain
Source

# 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
- 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, …)

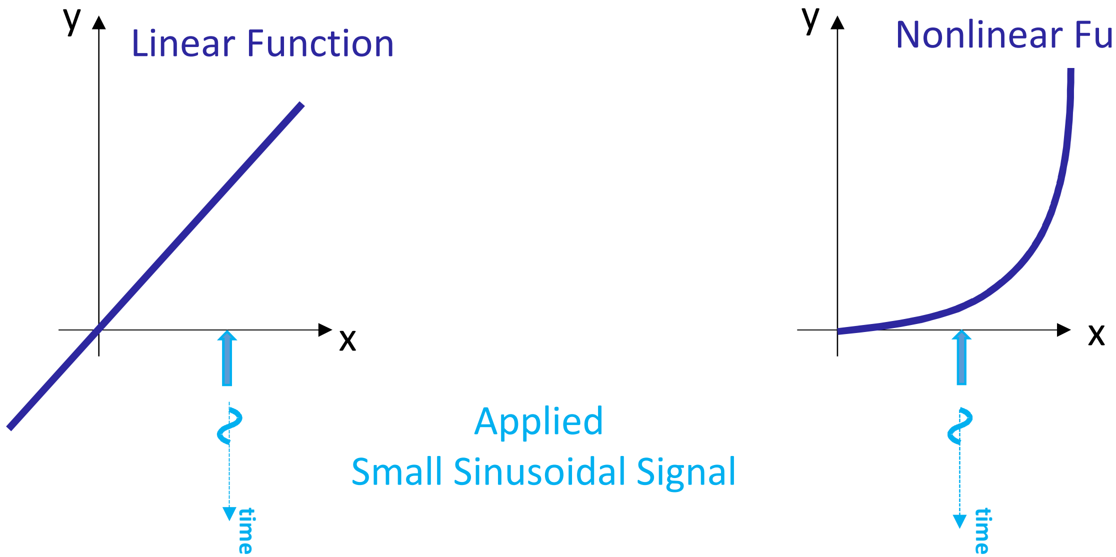


# I - Differences Active/Passive & Linear/Nonlinear

## 1) Power Losses / Gain / Bias

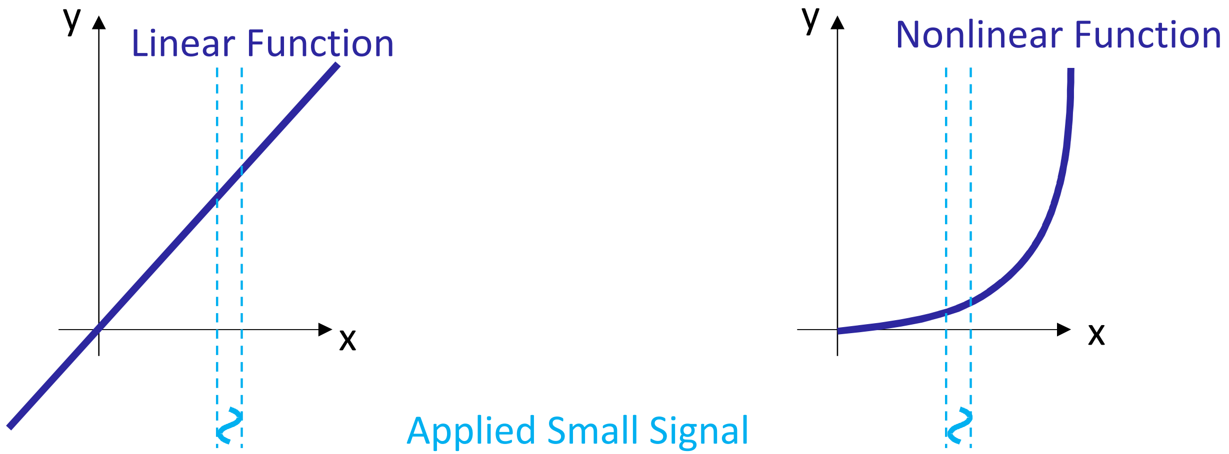
- A passive circuit cannot give power gain but only losses
- A passive circuit is linear and its response does not depend on the signal amplitude
- On the contrary, a power gain greater than unity is linked to active circuits and bias
- An active circuit can be linear or nonlinear depending on the signal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



# I - Differences Active/Passive & Linear/Nonlinear

## 1) Power Losses / Gain / Bias

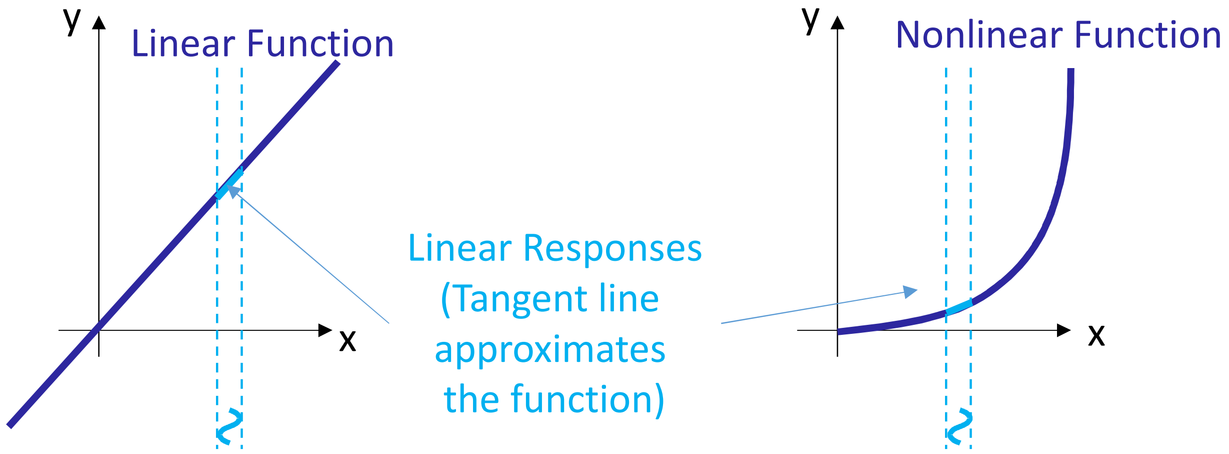
- A passive circuit cannot give power gain but only losses
- A passive circuit is linear and its response does not depend on the signal amplitude
- On the contrary, a power gain greater than unity is linked to active circuits and bias
- An active circuit can be linear or nonlinear depending on the signal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



# 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, …)

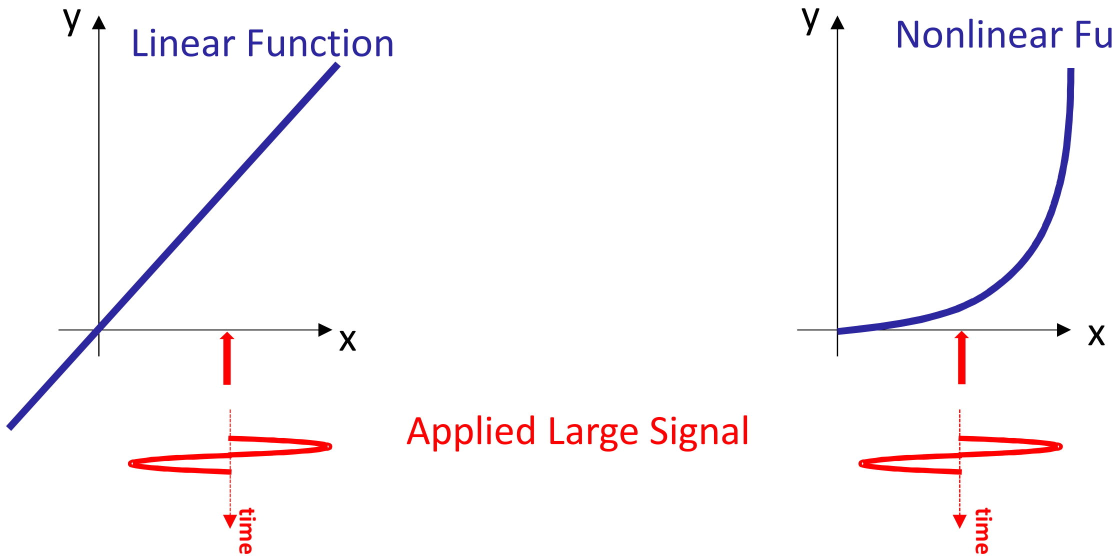



**Linear and Nonlinear circuits give a linear response to small signals**

# I - Differences Active/Passive & Linear/Nonlinear

## 1) Power Losses / Gain / Bias

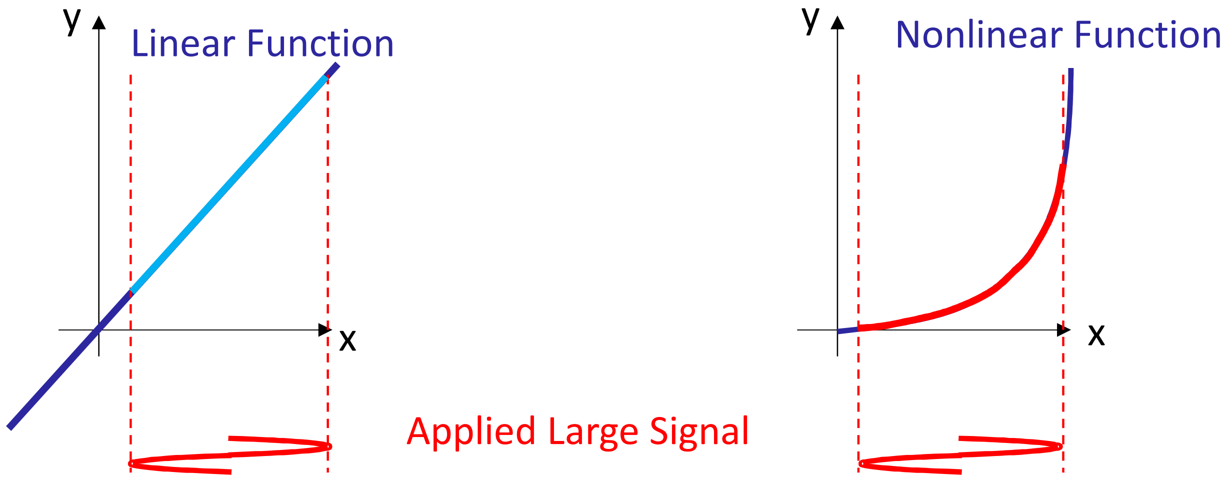
- A passive circuit cannot give power gain but only losses
- A passive circuit is linear and its response does not depend on the signal amplitude
- On the contrary, a power gain greater than unity is linked to active circuits and bias
- An active circuit can be linear or nonlinear depending on the signal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



# I - Differences Active/Passive & Linear/Nonlinear

## 1) Power Losses / Gain / Bias

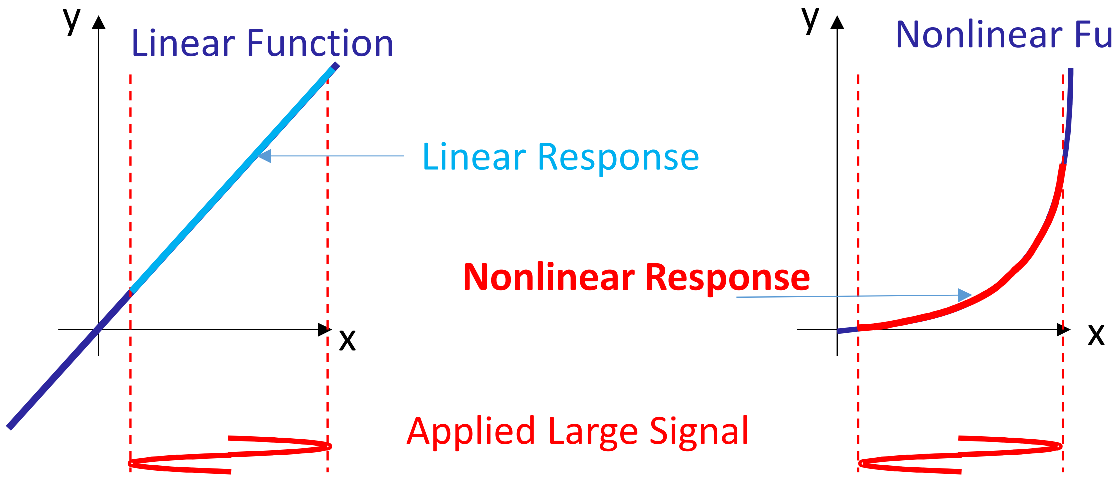
- A passive circuit cannot give power gain but only losses
- A passive circuit is linear and its response does not depend on the signal amplitude
- On the contrary, a power gain greater than unity is linked to active circuits and bias
- An active circuit can be linear or nonlinear depending on the signal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



# 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, …)**



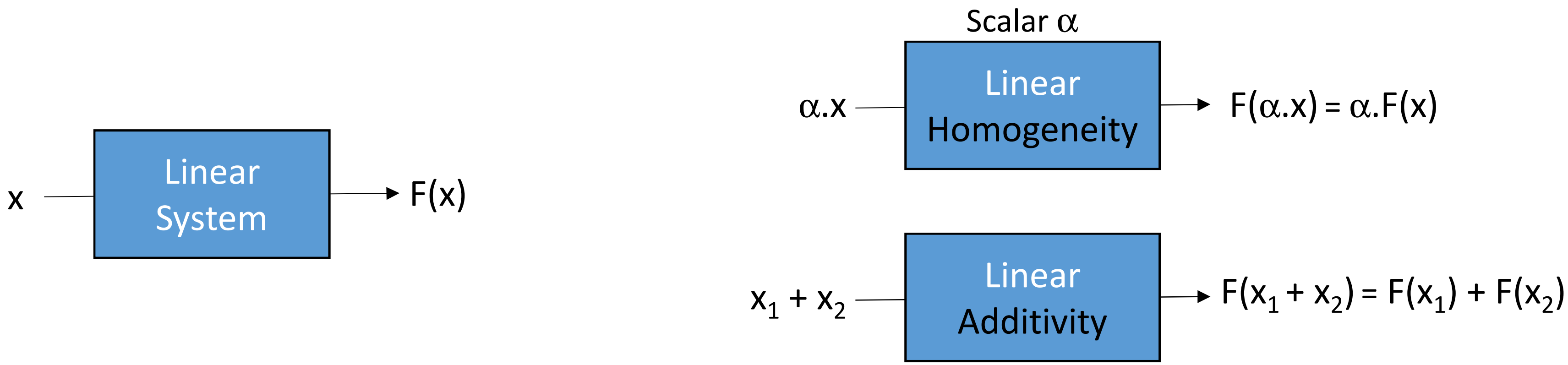

**Linear circuits remain linear in the case of large signals**

**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**




Sparameter

# I - Differences Active/Passive & Linear/Nonlinear

HPA (High Power Amplifiers)

## 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.

$e_1 + e_2 + \dots + e_n$ → Linear System → $S = ?$

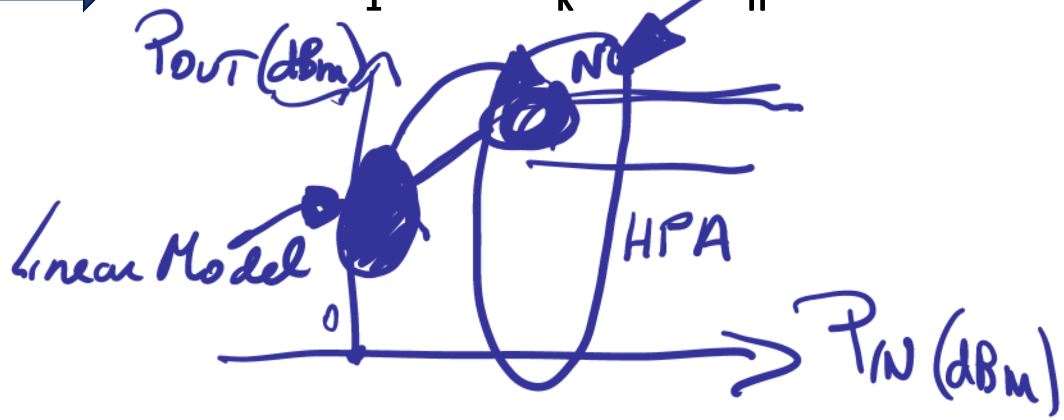

$e_1$ → Linear System → $S_1$, with $e_i = 0 \quad \forall\, i \neq 1$

and so on

$e_k$ → Linear System → $S_k$, with $e_i = 0 \quad \forall\, i \neq k$

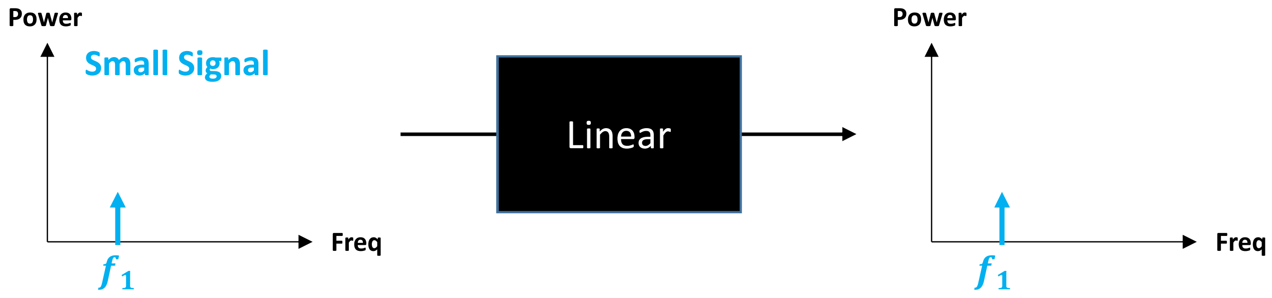
$e_n$ → Linear System → $S_n$, with $e_i = 0 \quad \forall\, i \neq n$

$$S = S_1 + \dots + S_k + \dots + S_n$$



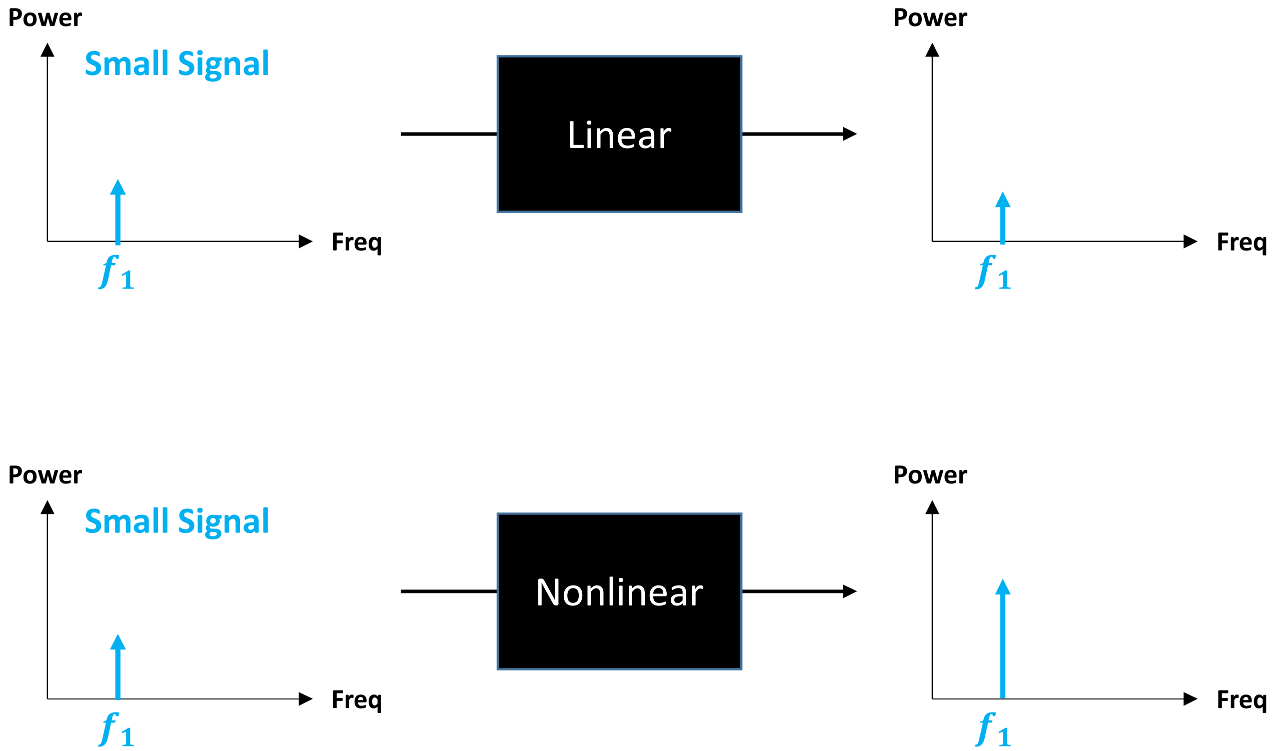
# I - Differences Active/Passive & Linear/Nonlinear

## 2) Linearity / Non Linearity (single carrier)



# I - Differences Active/Passive & Linear/Nonlinear

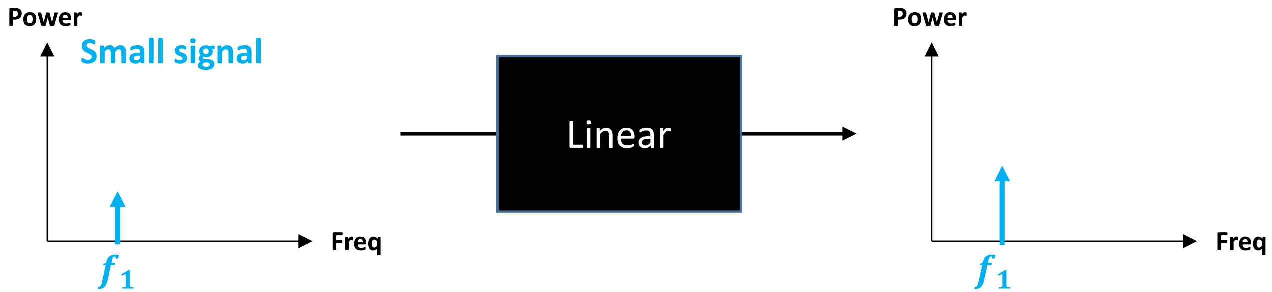
## 2) Linearity / Non Linearity (single carrier)




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

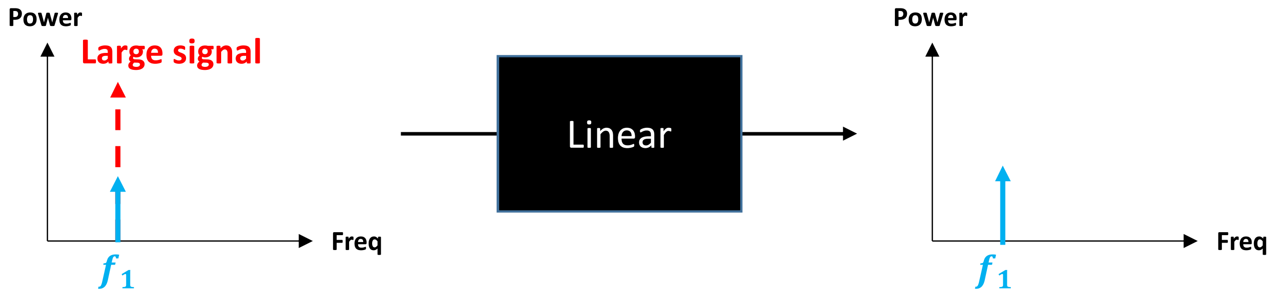
# I - Differences Active/Passive & Linear/Nonlinear

2) Linearity / Non Linearity (single carrier)



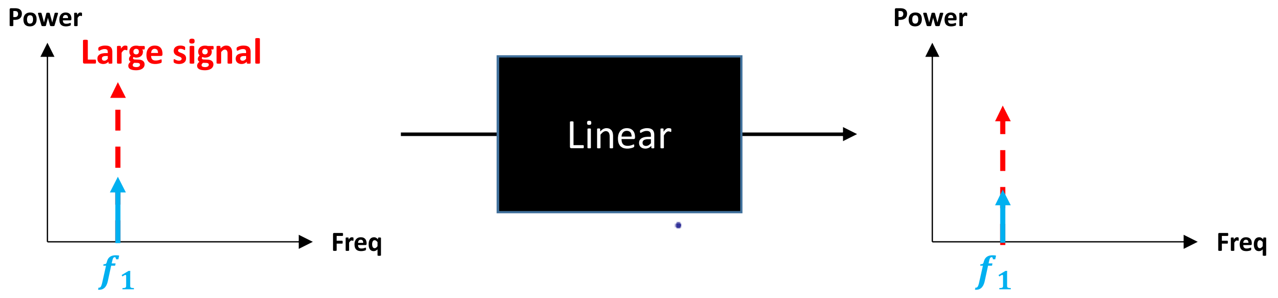
# I - Differences Active/Passive & Linear/Nonlinear

2) Linearity / Non Linearity (single carrier)



# I - Differences Active/Passive & Linear/Nonlinear

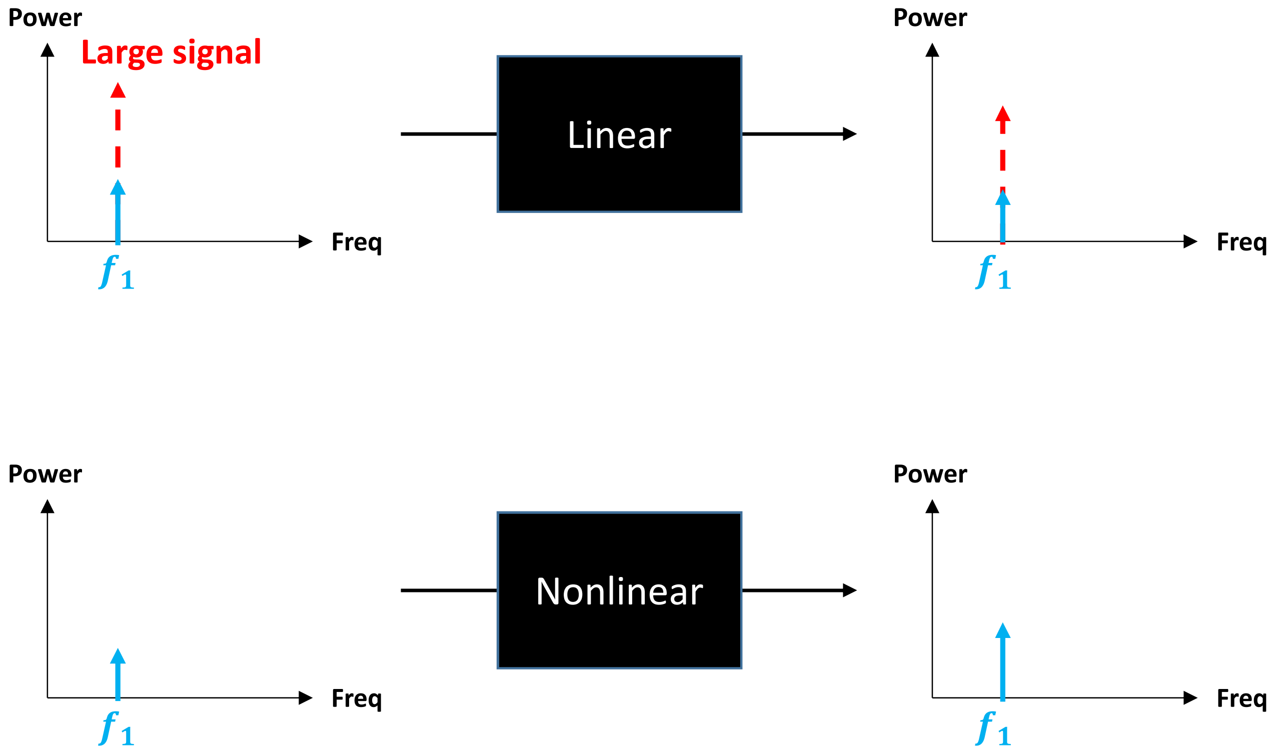
## 2) Linearity / Non Linearity (single carrier)




**The response remains linear**

# I - Differences Active/Passive & Linear/Nonlinear

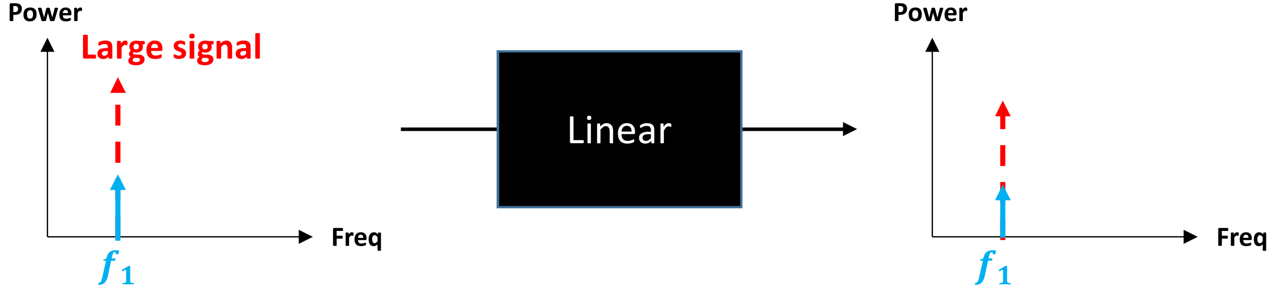
## 2) Linearity / Non Linearity (single carrier)



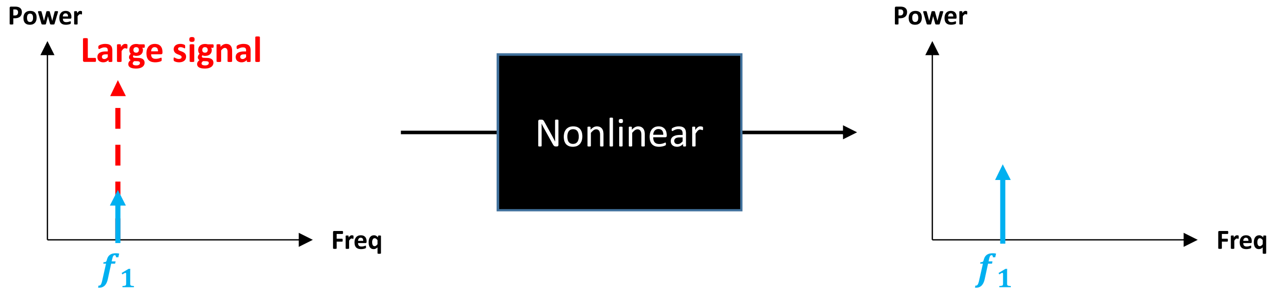

The response remains linear

# I - Differences Active/Passive & Linear/Nonlinear

## 2) Linearity / Non Linearity (single carrier)

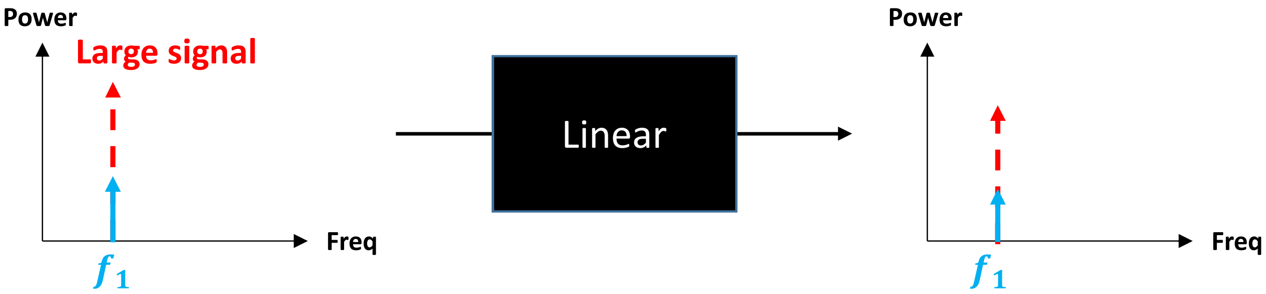



**The response remains linear**

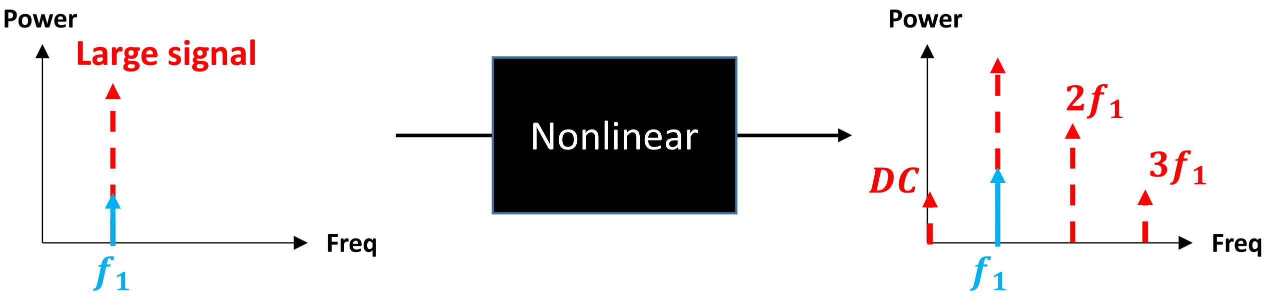


# I - Differences Active/Passive & Linear/Nonlinear

2) Linearity / Non Linearity (single carrier)




**The response remains linear**



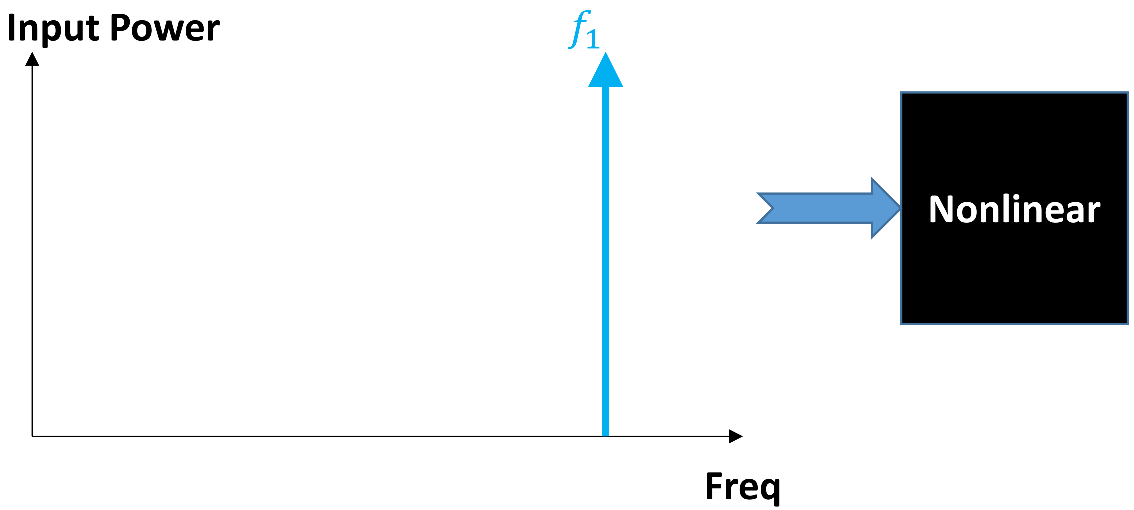

**The response is nonlinear (generation of harmonics)**

# 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**

$$x(t) = A\,cos(\omega_1 t)$$


$$y(t) = a.x + b.x^2 + c.x^3$$

# 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:

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

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

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

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

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

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

# I - Differences Active/Passive & Linear/Nonlinear

## 3) Frequency generation of nonlinear devices

### a) Single carrier

**Illustration using a 3rd order polynomial nonlinearity**

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

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

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

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

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

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

$\boxed{a.x} \rightarrow a.A\ cos(\omega_1 t)$

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

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

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

**Even Nonlinearity Order → Even Harmonics less than or equal to the order**

*Example of $cos^2$ (Nonlinearity Order 2 → Harmonics 0 and 2)*

**Odd Nonlinearity Order → Odd Harmonics less than or equal to the order**

*Example of $cos^3$ (Nonlinearity Order 3 → Harmonics 3 and 1)*

→ **Without calculation of $cos^4$, we know that a nonlinearity order of 4 → Harmonics 4, 2 and 0**

**Without calculation of $cos^5$, 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**

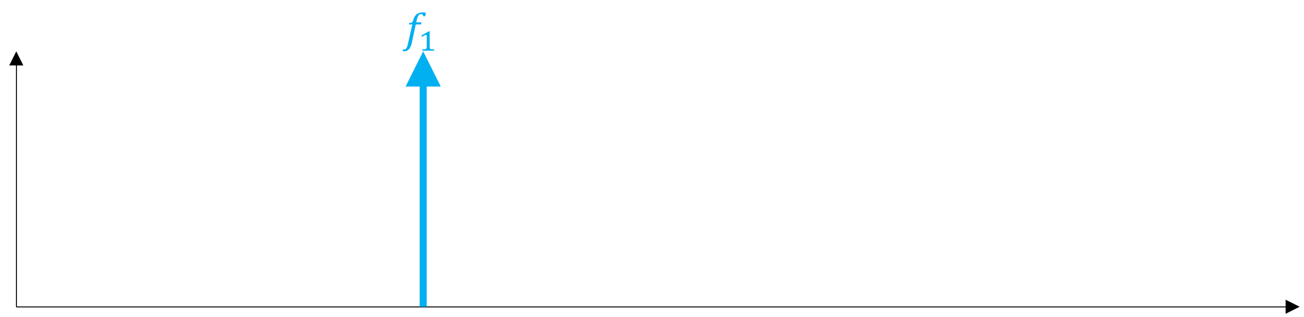
$x(t) = A\,cos(\omega_1 t)$ → **Nonlinear** → $y(t) = \boxed{a.x} + b.x^2 + c.x^3$

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

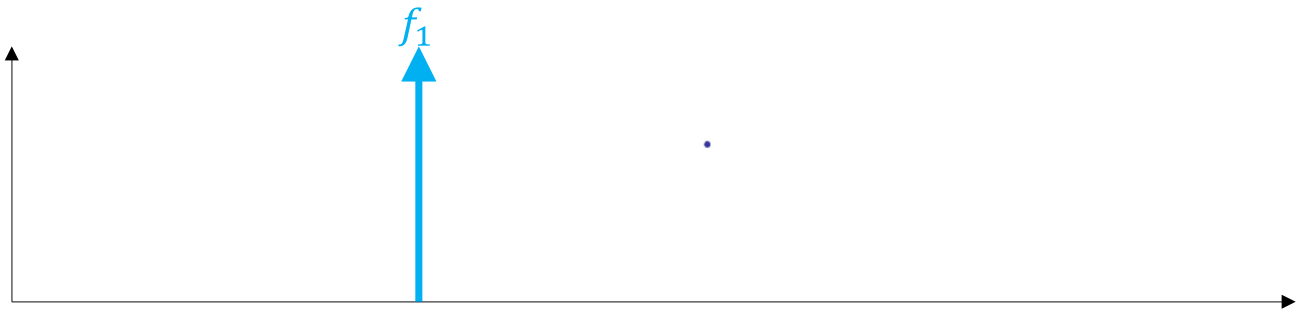
$$x(t) = A\,cos(\omega_1 t) \rightarrow \boxed{\text{Nonlinear}} \rightarrow y(t) = a.x + \boxed{b.x^2} + c.x^3$$

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

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

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

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



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

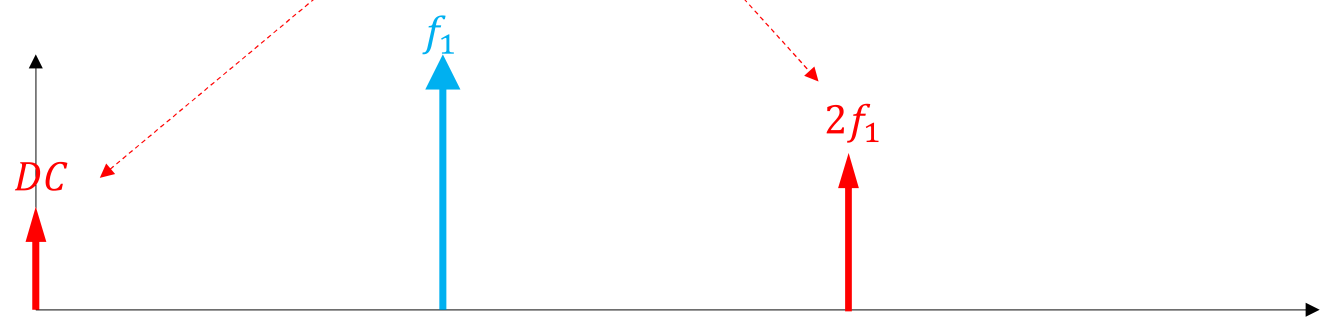
$$\frac{b.A^2}{2} + \frac{b.A^2}{2} cos(2\omega_1 t)$$

**2nd order of nonlinearity**
**→ Harmonics 0 and 2**

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

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

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



# I - Differences Active/Passive & Linear/Nonlinear

## 3) Frequency generation of nonlinear devices

### a) Single carrier

**Illustration using a 3rd order polynomial nonlinearity**

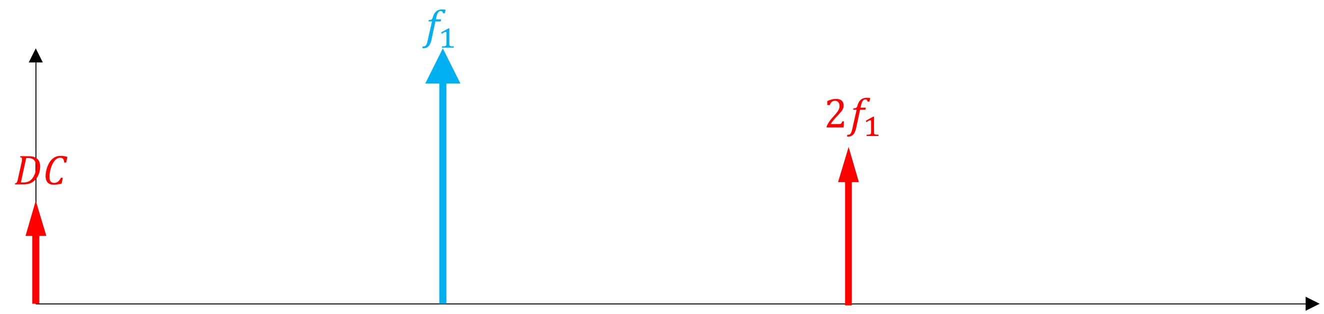
$x(t) = A\, cos(\omega_1 t)$ → **Nonlinear** → $y(t) = a.x + b.x^2 + \boxed{c.x^3}$

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

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

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

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



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

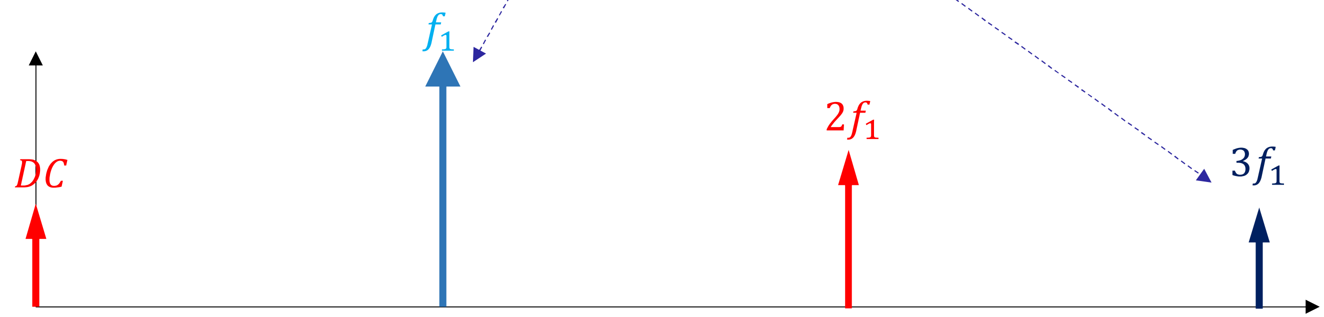
$$\frac{3c.A^3}{4}cos(\omega_1 t) + \frac{c.A^3}{4}cos(3\omega_1 t)$$

**3rd order of nonlinearity**
**→ Harmonics 1 and 3**

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

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

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

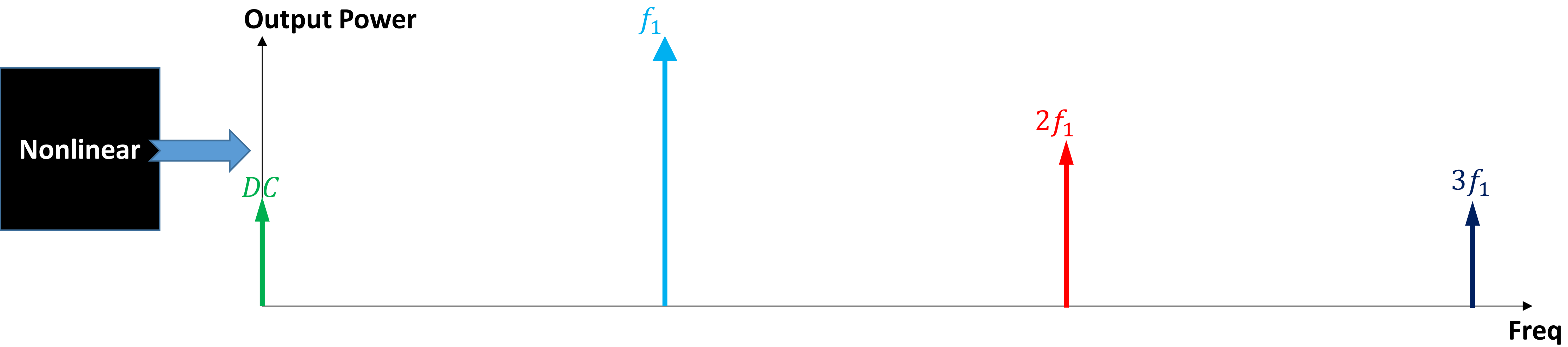


# I - Differences Active/Passive & Linear/Nonlinear

## 3) Frequency generation of nonlinear devices

### a) Single carrier

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



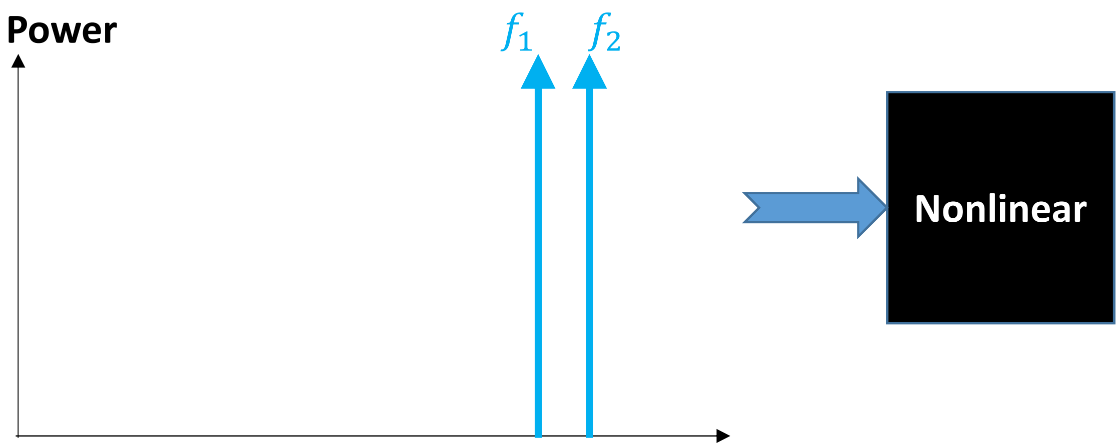
# I - Differences Active/Passive & Linear/Nonlinear

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



# I - Differences Active/Passive & Linear/Nonlinear

HFSS (electromagnetic CAD)
ADS (circuit CAD)

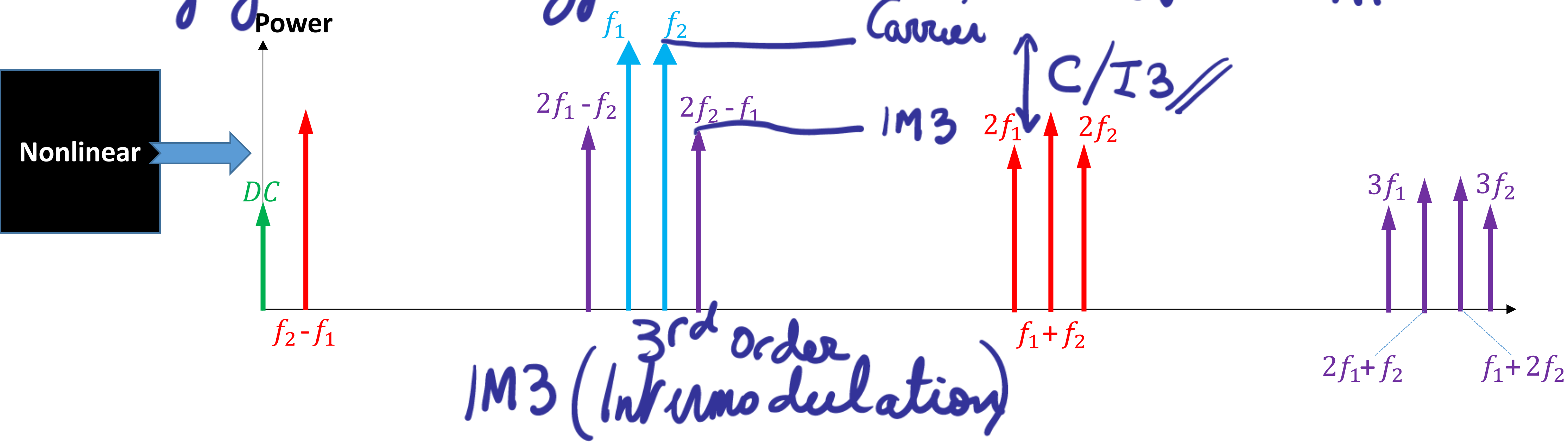
## 3) Frequency generation of nonlinear devices

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

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

ADS (Advanced Design System)
Keysight Technology ← Agilent Technology ← HP

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



# I - Differences Active/Passive & Linear/Nonlinear

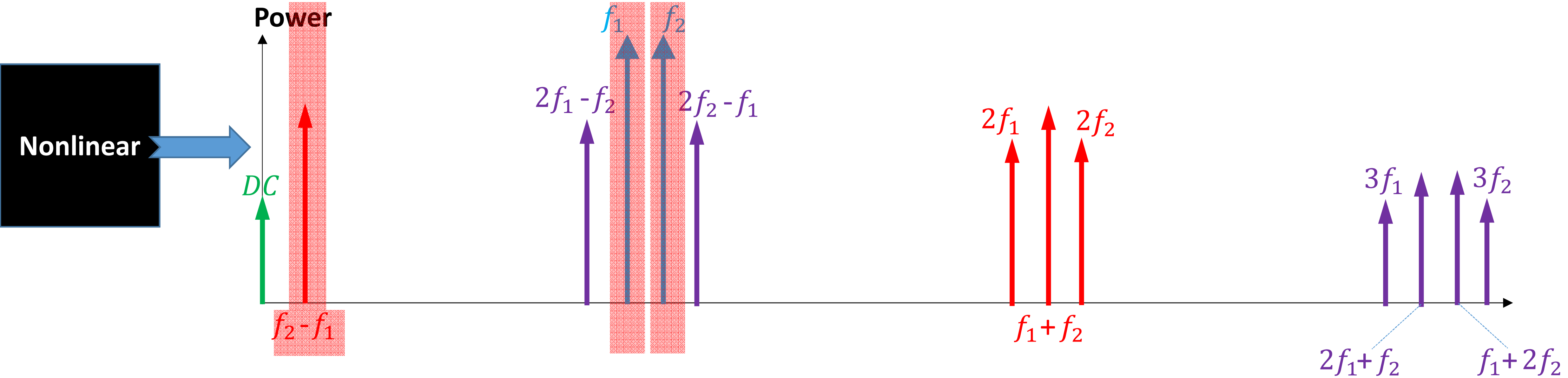
3) Frequency generation of nonlinear devices

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

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



# I - Differences Active/Passive & Linear/Nonlinear

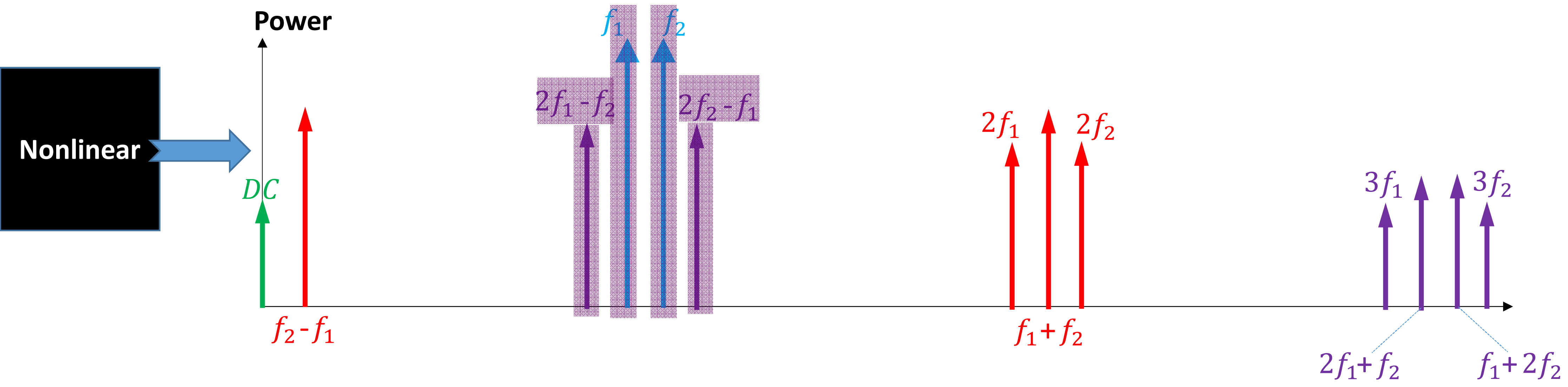
3) Frequency generation of nonlinear devices

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**



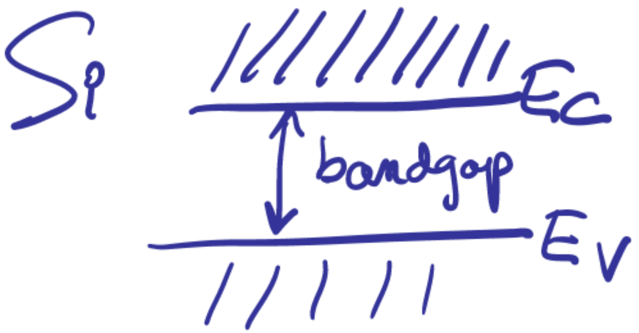
# II – Brief Overview of High-Frequency Active Devices for Power Amplifiers

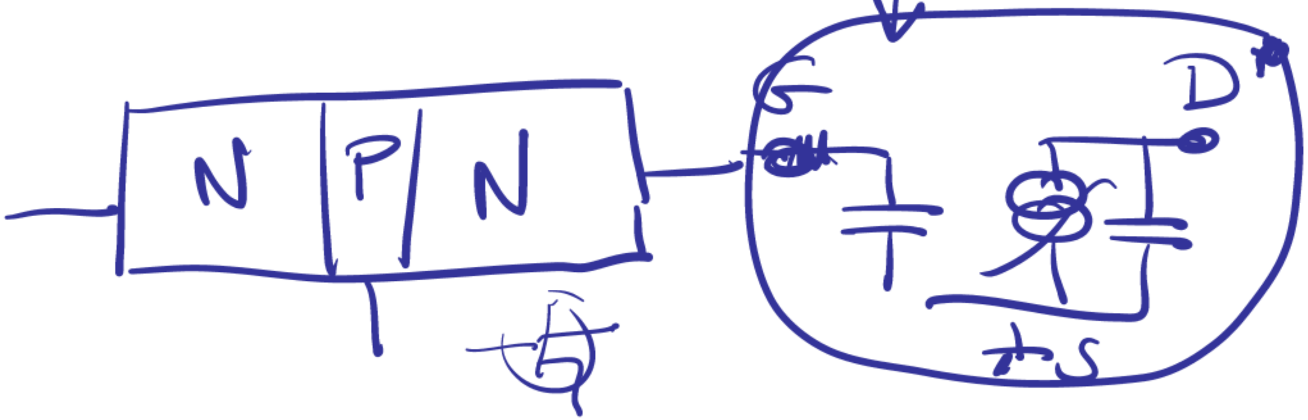
1) Low Frequency (up to 100MHz)
    - Well established consumer electronics / High level of integration / Low cost / High volumes
    - Silicon Bipolar Transistors / MOSFETs (Metal Oxyde Semiconductor FETs / BiCMOS …)

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)

GaAs HEMTs

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



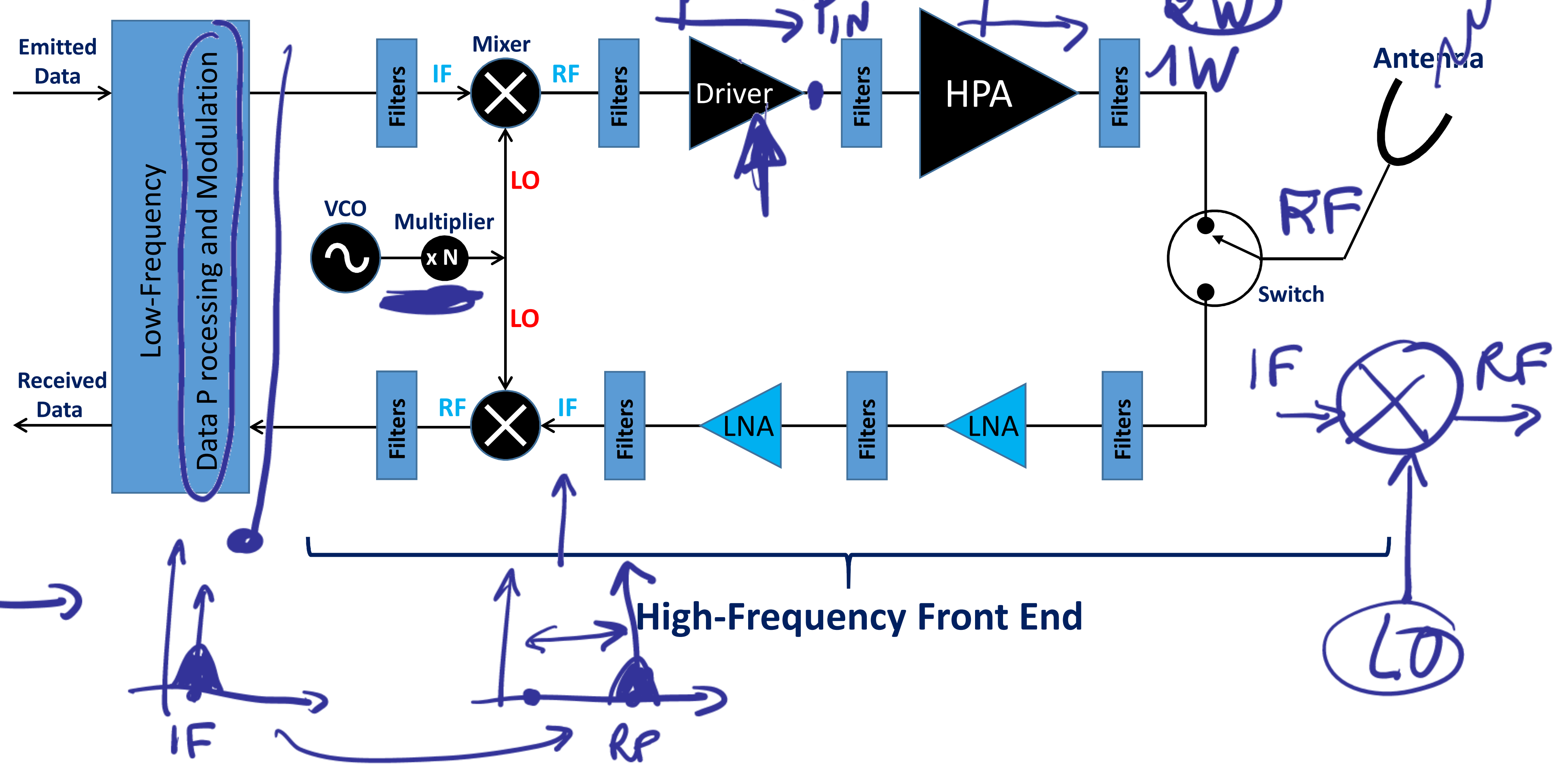



VCO ( Voltage Controlled Oscillator) LO → fosc
VCO → fosc



# III – High-Frequency Active Circuits in Communication Systems

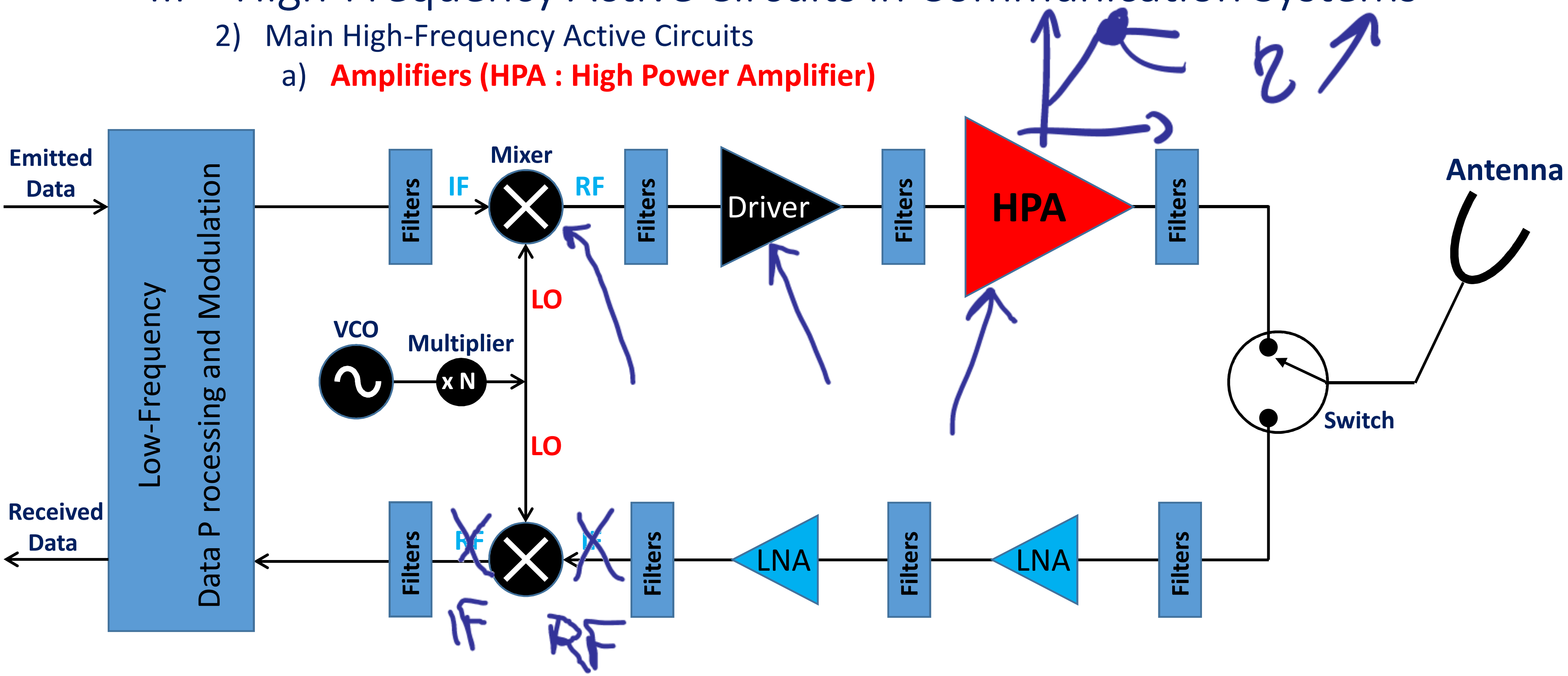
1) Example (Simplified Block Diagram of E/R Functions)



# III – High-Frequency Active Circuits in Communication Systems

## 2) Main High-Frequency Active Circuits

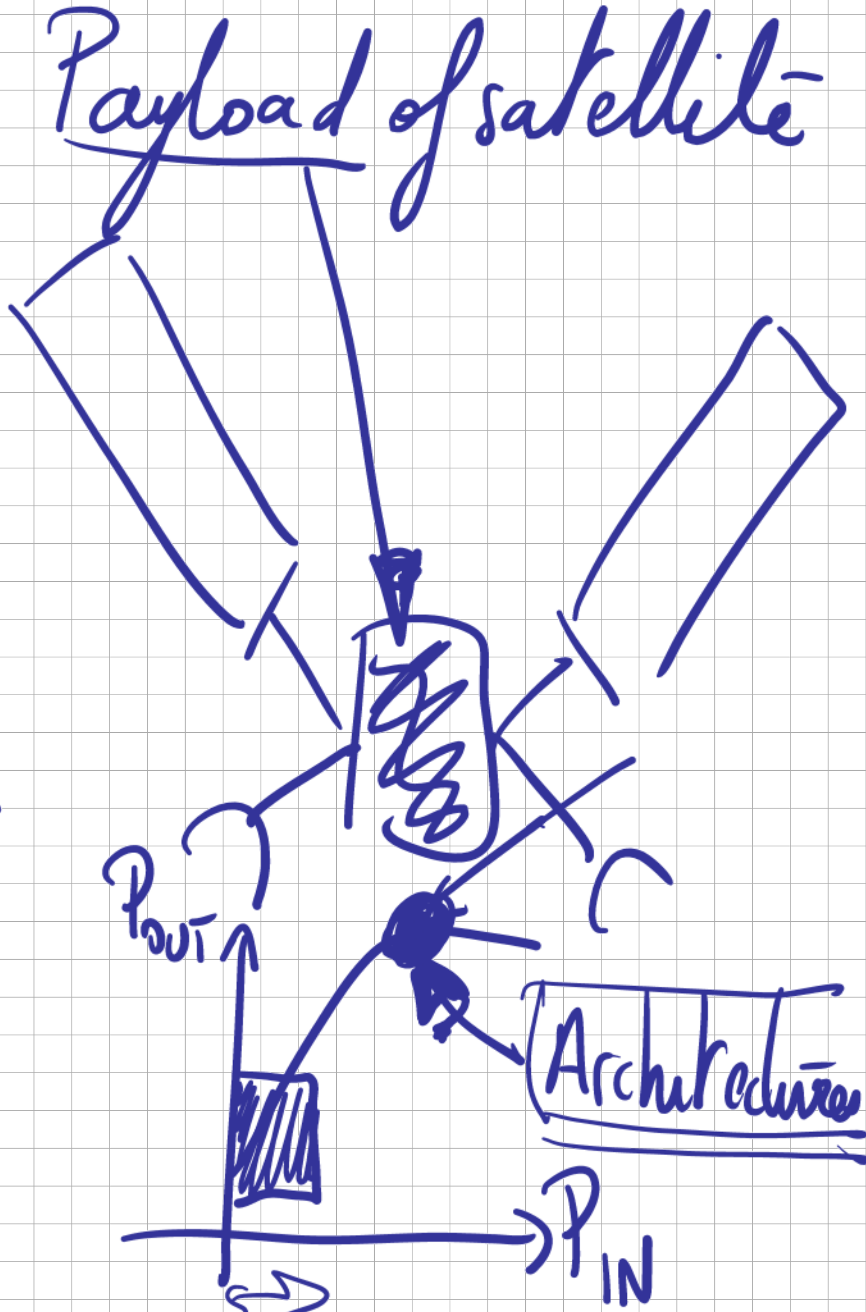
### a) Amplifiers (HPA : High Power Amplifier)

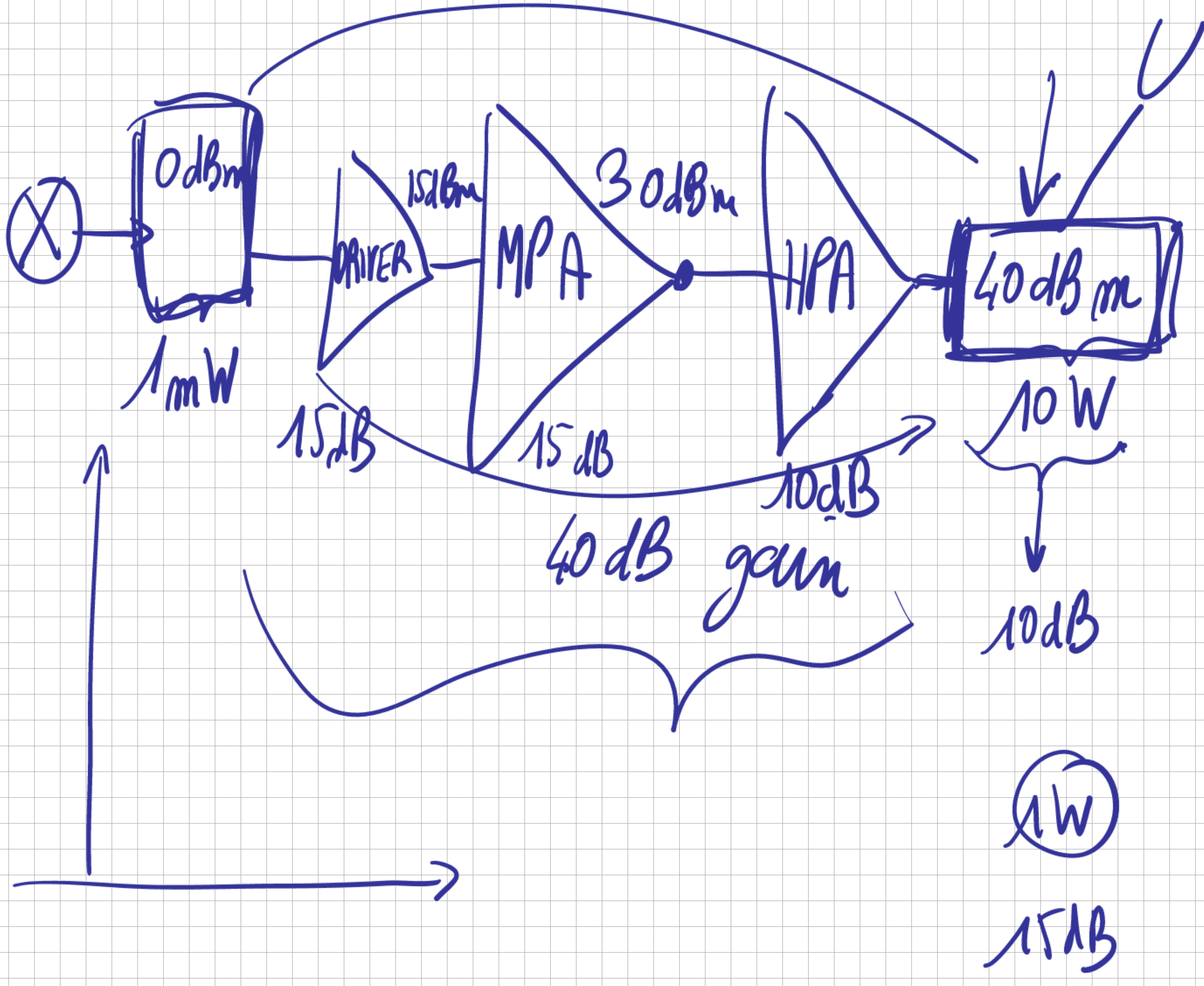



High-Frequency Front End

# Thales Alenia Space (Toulouse)

HPAs

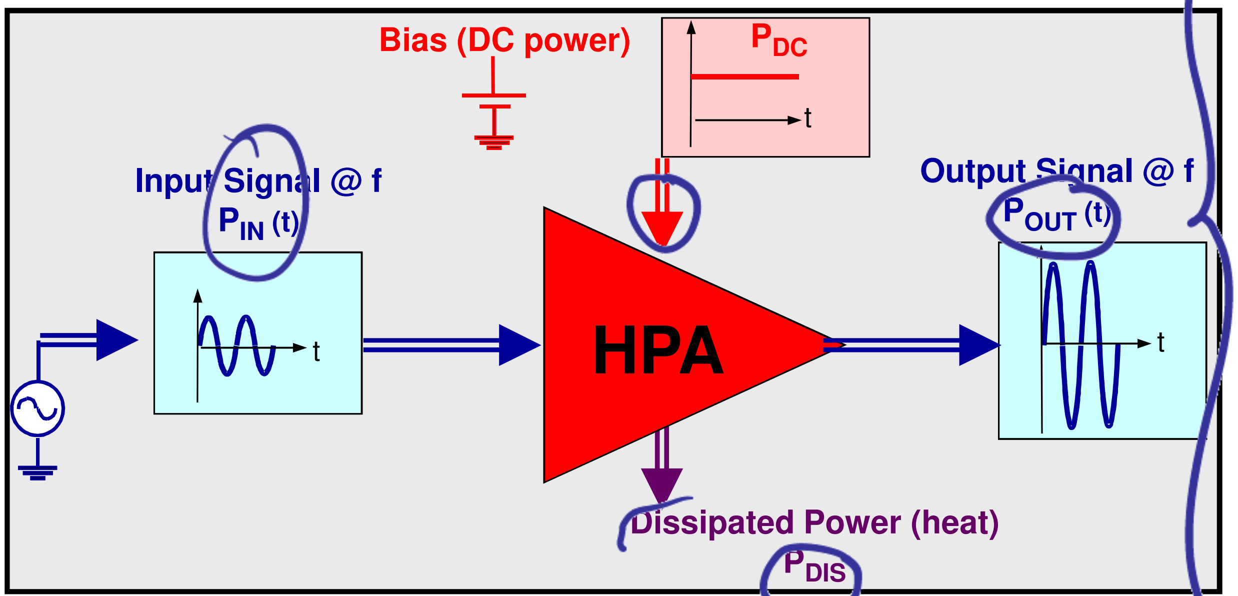




0dBm
1mW
DRIVER
15dBm
15dB
MPA
30dBm
15dB
HPA
10dB
40dBm
10W
40dB gain
10dB
1W
15dB

# III – High-Frequency Active Circuits in Communication Systems

## 2) Main High-Frequency Active Circuits

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




$$\sum \text{Input Powers} = \sum \text{Output Powers}$$

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

**Power gain** and **Power Added Efficiency**

$G = P_{OUT} / P_{IN}$ and $PAE = ( P_{OUT} – P_{IN} ) / P_{DC}$

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

**Dissipated Power** **Temperature** Increase

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

100%

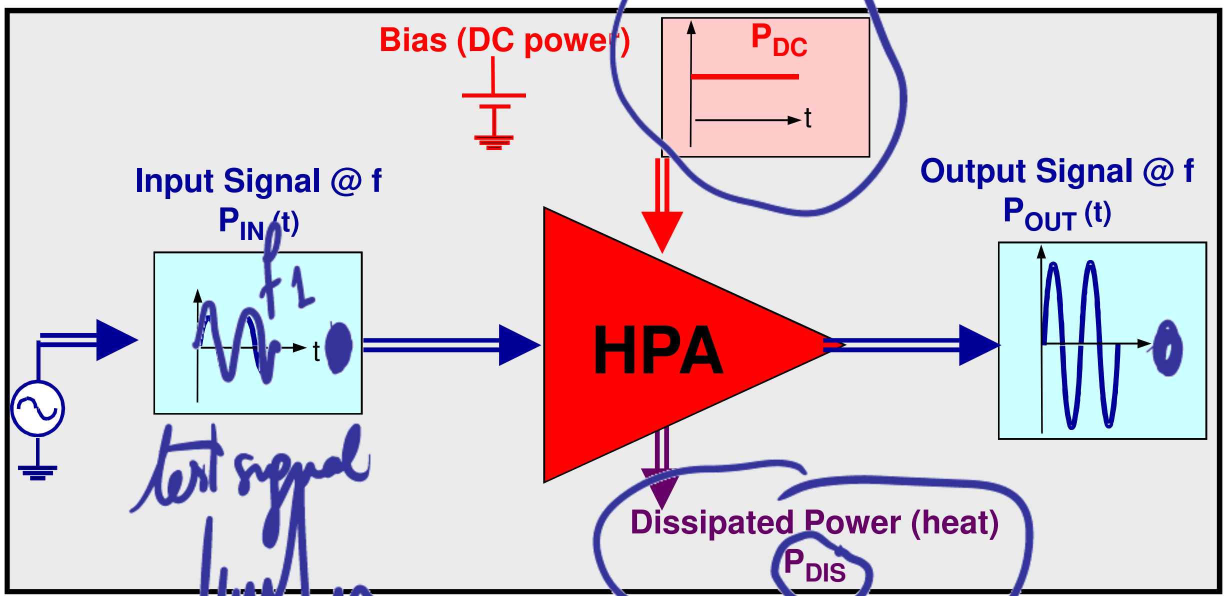
# III – High-Frequency Active Circuits in Communication Systems

## 2) Main High-Frequency Active Circuits

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

$$\frac{P_{OUT}(t) - \cancel{P_{IN}(t)}}{P_{DC}}$$

Battery




f1

test signal

**Only one accurate definition of efficiency**

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

**Power Efficiency**

$\eta = P_{OUT} / \cancel{P_{IN}}$

$P_{DC}$

**Power Added Efficiency**

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

$1W - \cancel{0{,}1W}$

$1W - 2W$

PAE ↗ $P_{DC}$ ↓

$\eta$

T ↓

20 W

DC

40W → $P_{DIS}$

GaAs HEMT

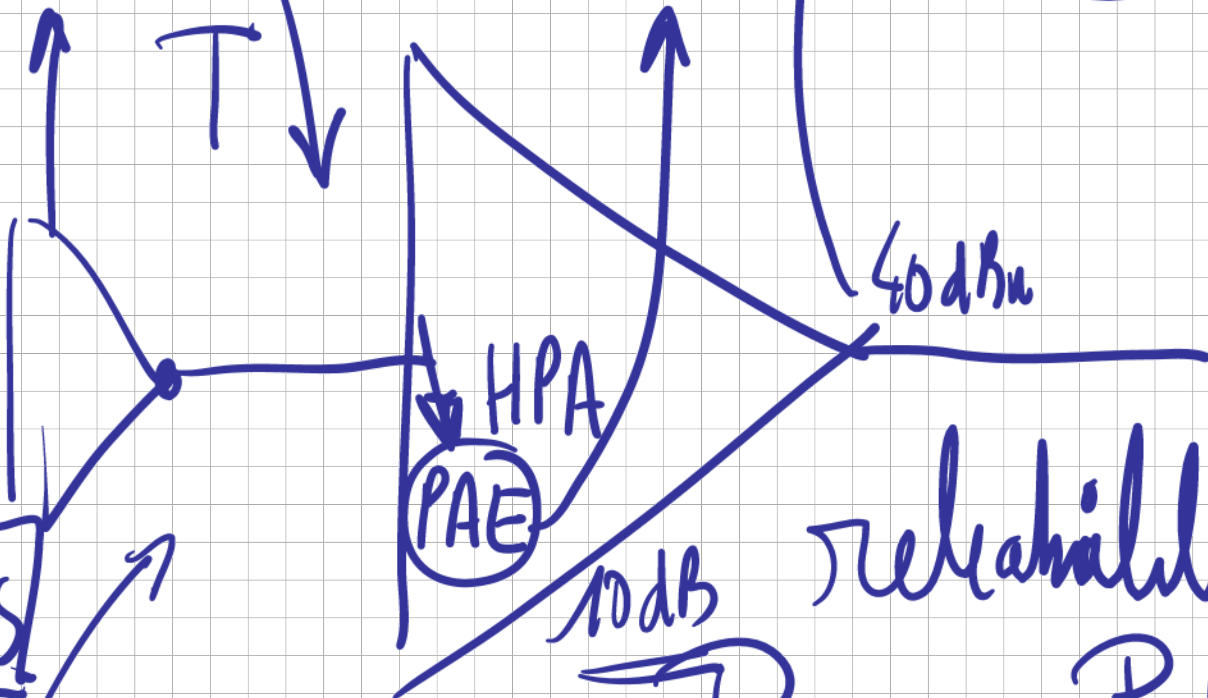
100W @ 2GHz

60% 70%

10W @ 2G

40% 80%

10 W




reliability

LDMOS

GaAs HEMTs

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

PAE

TWT

$PAE = 50\% = 0{,}5$ → $P_{DC} = \frac{10W}{0.5}$

PAE = ~~50%~~ 25% → $P_{DC} = 40\,W$

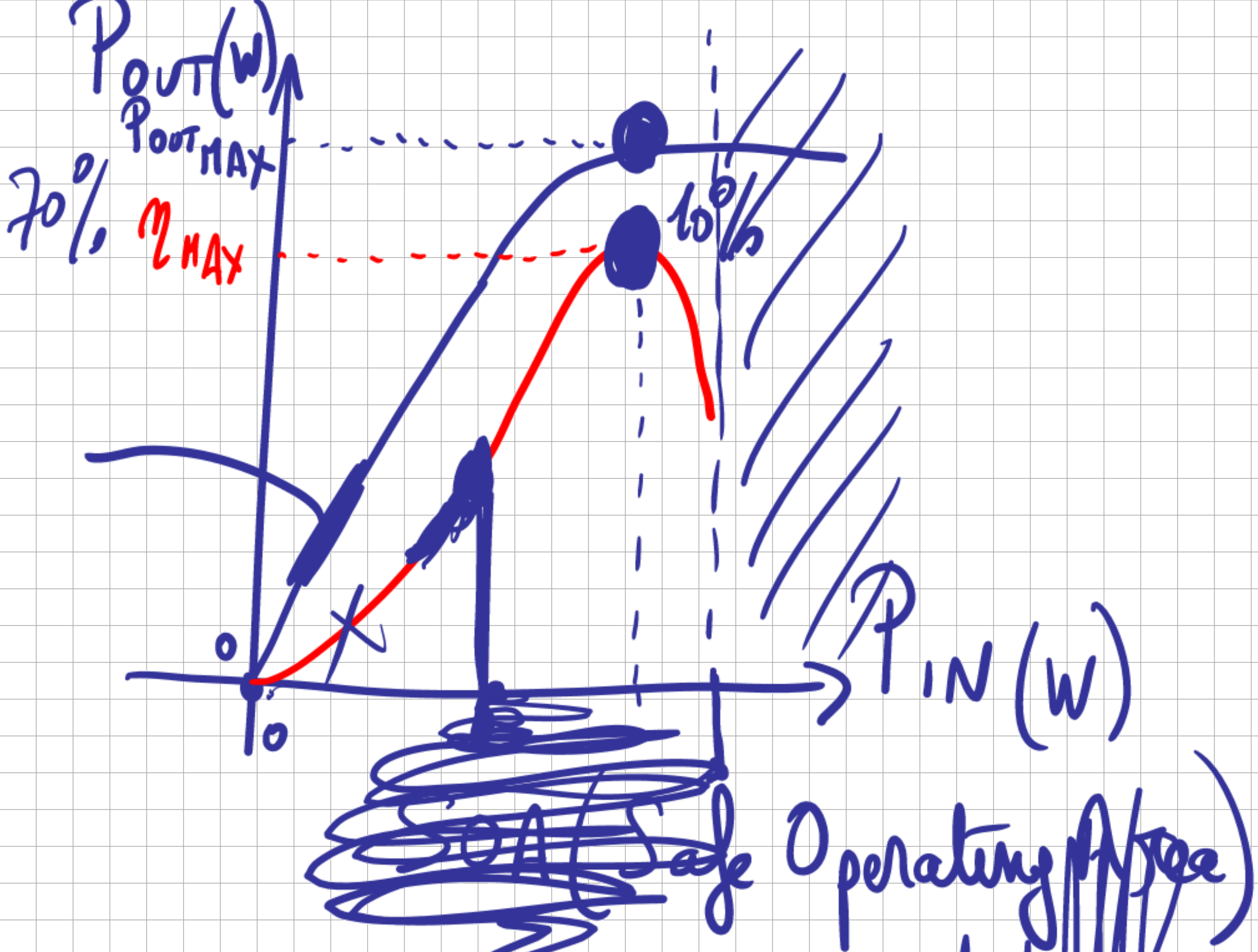
HPA using transistors

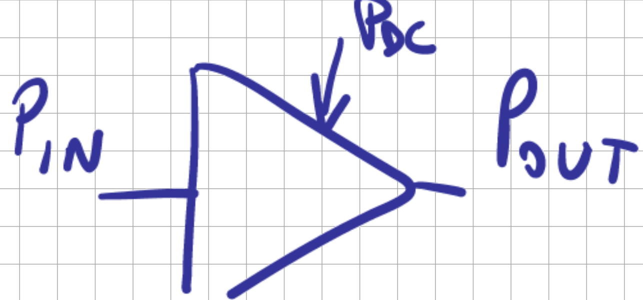
→ SSPA (Solid State Power Amplifiers)

TWT (Travelling Wave Tubes) Size ↑

Satellite ( Cost < (Reliability)

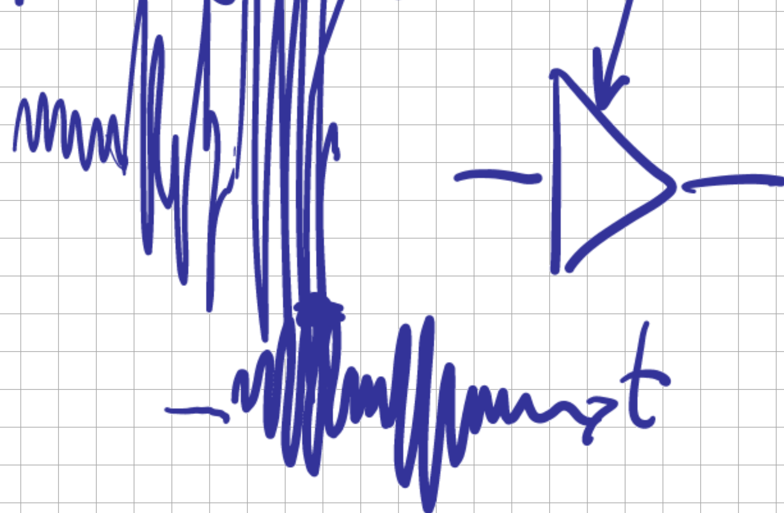
Mobile Phone ( Cost > Reliability)

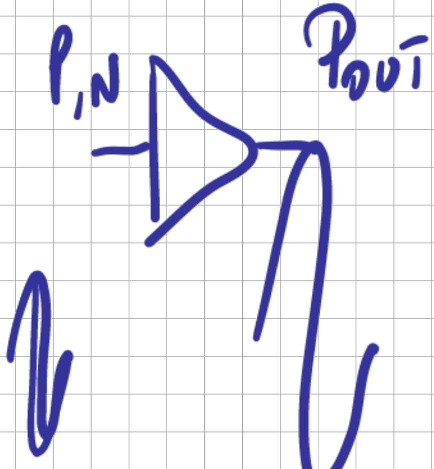



$$P_{OUT} = G\,P_{IN}$$

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

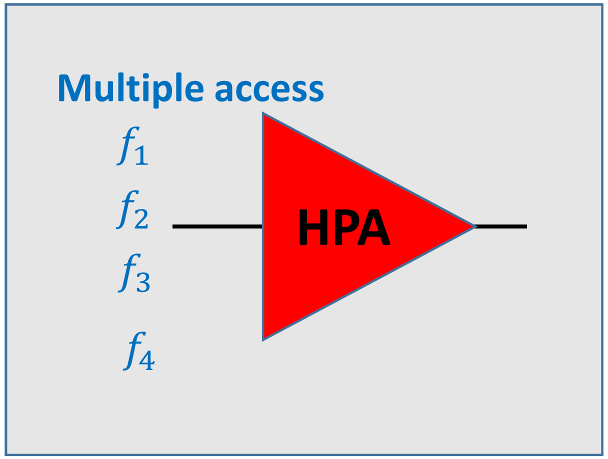



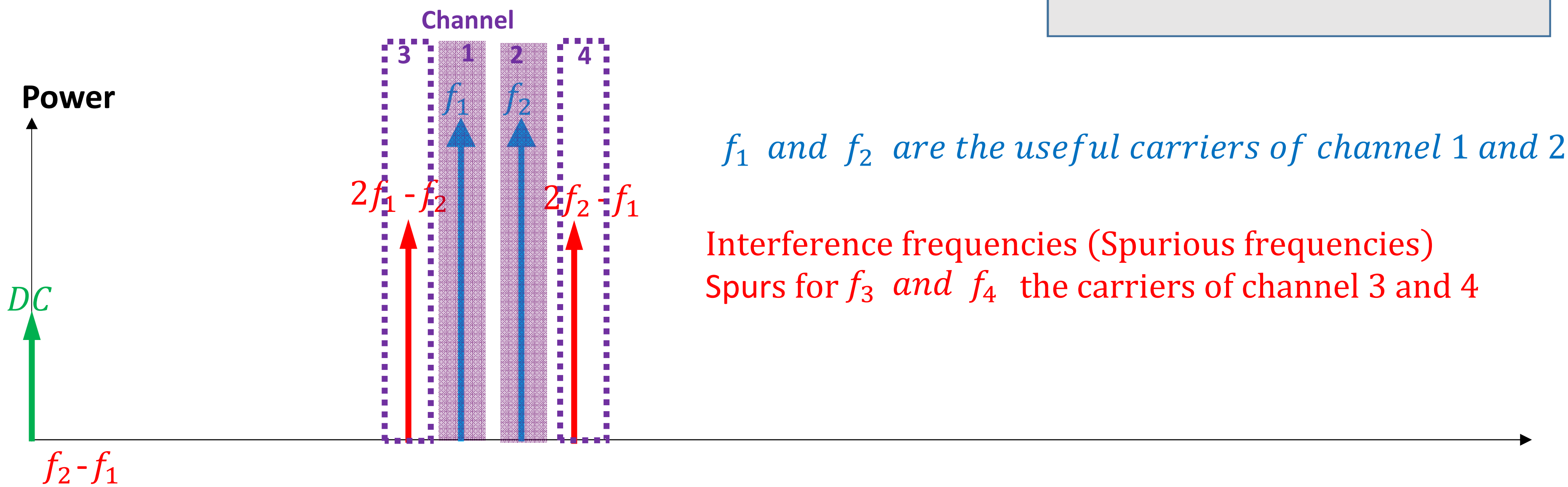



# Intermodulation products for power amplifiers

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

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

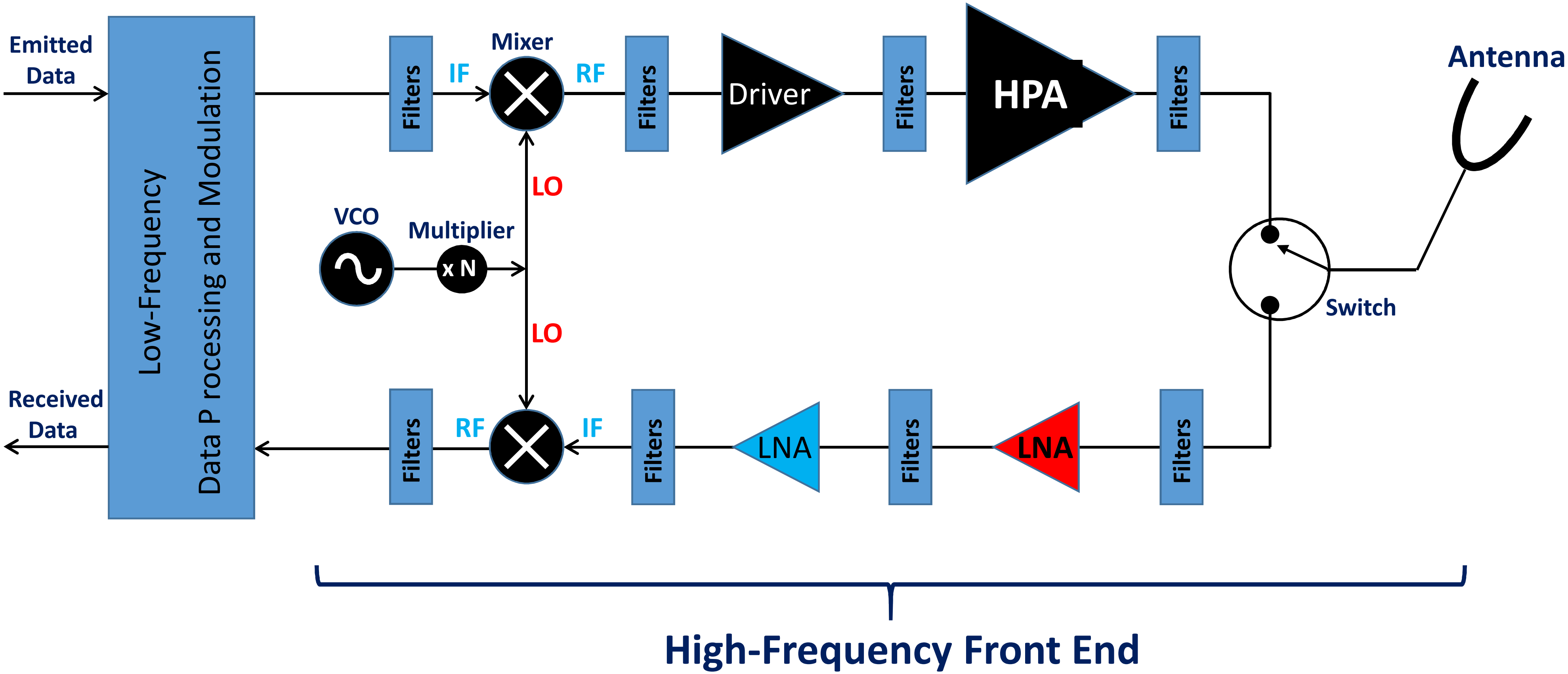


# III – High-Frequency Active Circuits in Communication Systems

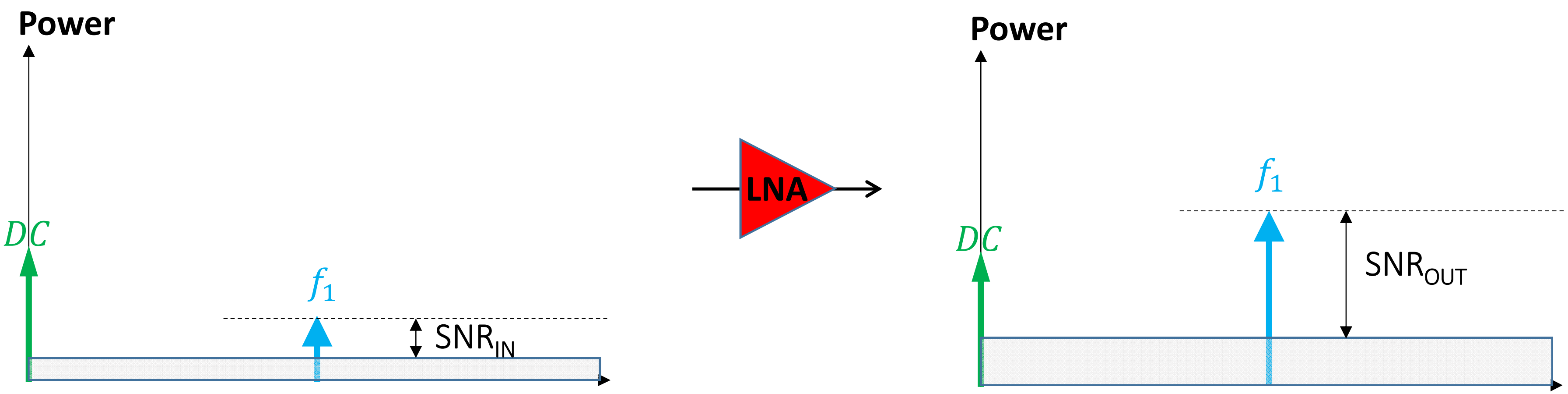
## 2) Main High-Frequency Active Circuits

### 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

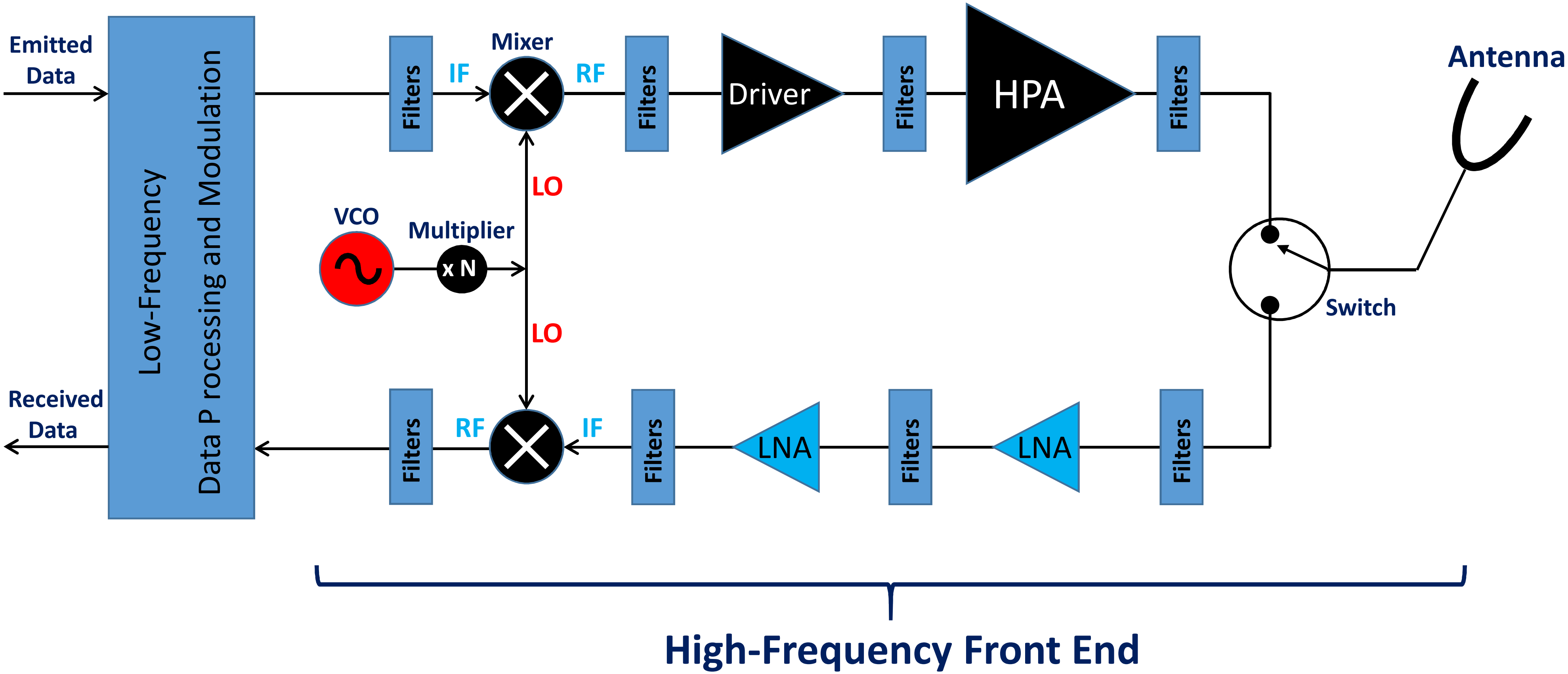



Low noise transistor technology

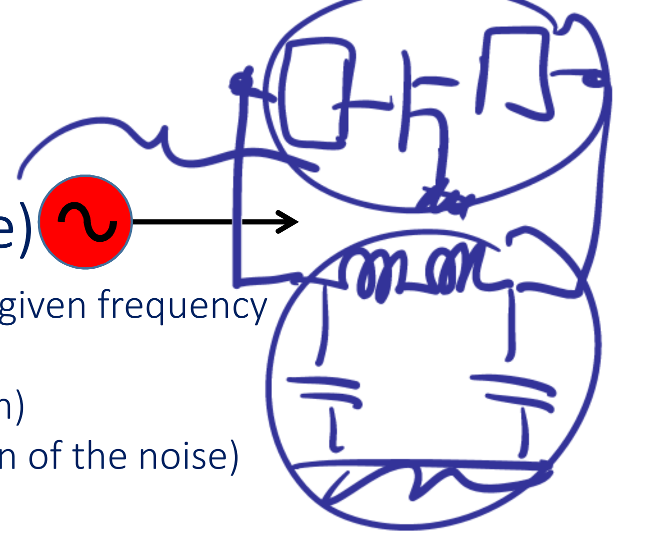
# III – High-Frequency Active Circuits in Communication Systems

## 2) Main High-Frequency Active Circuits

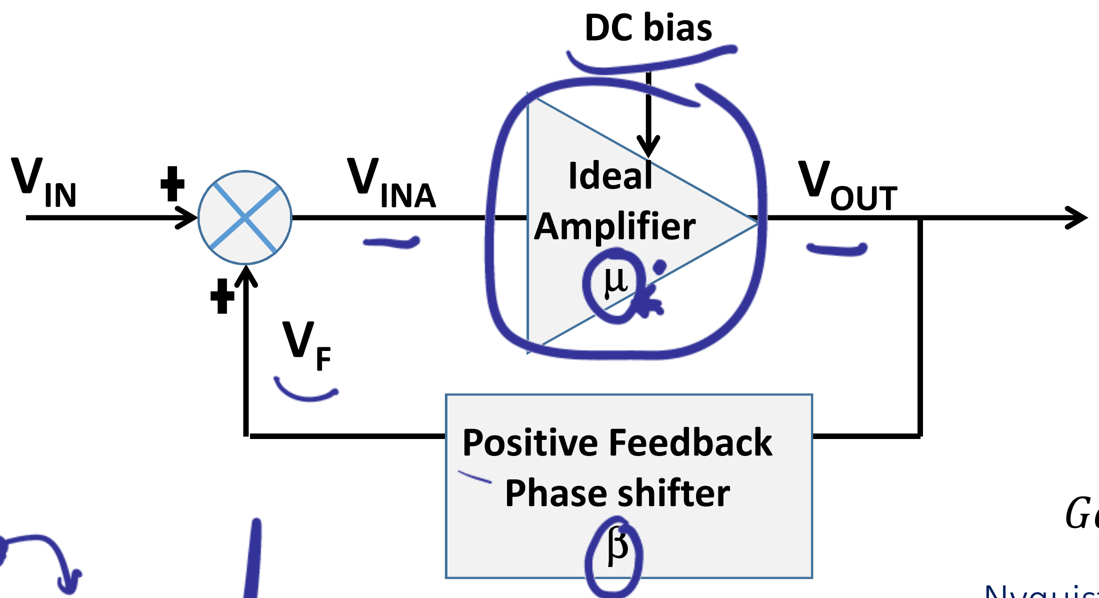
### c) Oscillators (LO : Local Oscillator) (VCO: Voltage Controlled Oscillator)



# 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)




**Closed-loop transfer function**

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

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

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

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

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

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

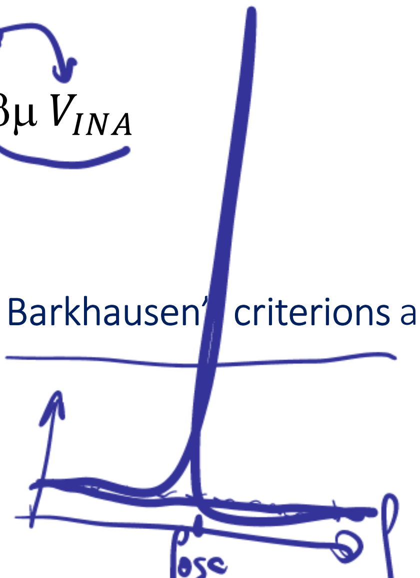
Nyquist Criterion:

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

$V_{OUT}$

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

$\sim 1$

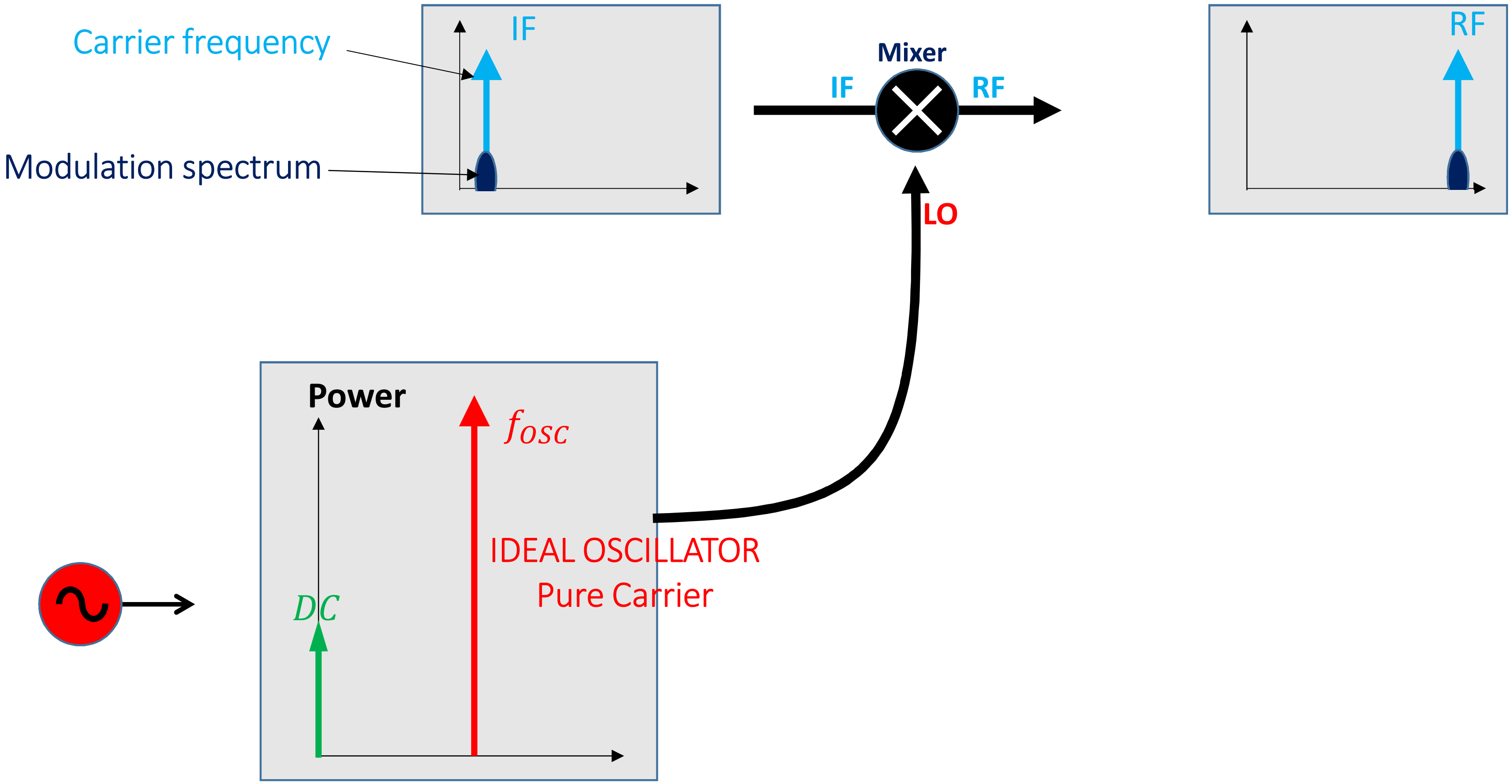





$\omega_{osc}$

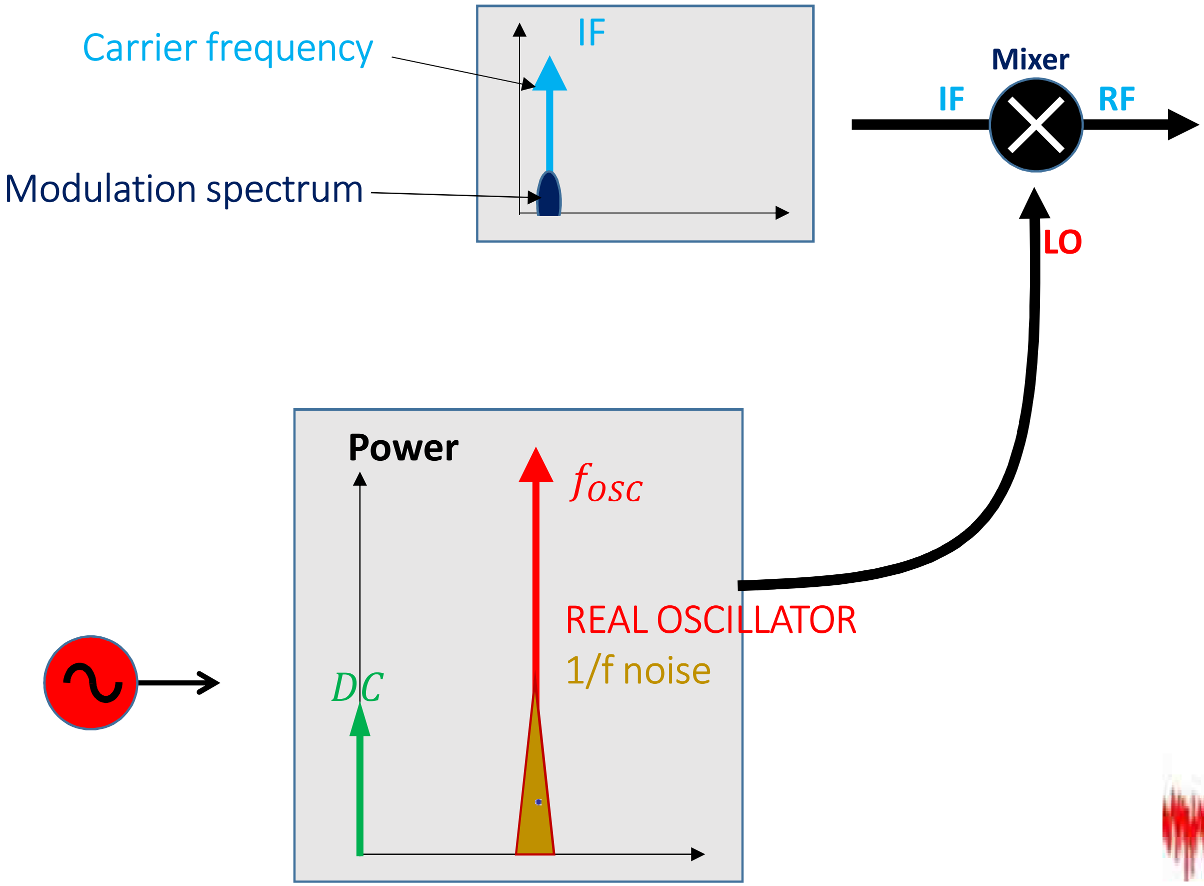
# Issue of 1/F noise of oscillators for ideal mixer operation

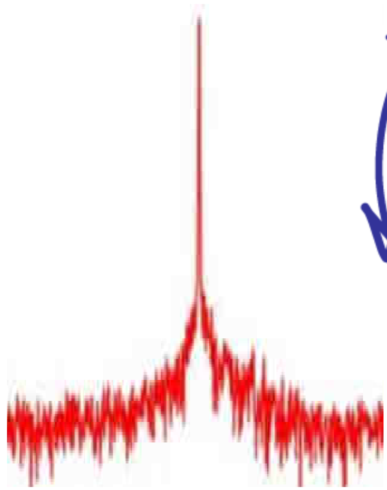
- Oscillations come from the control of the unstability for an amplifier(Gain → ∞) at a given frequency
- Optimisation of Oscillator's noise → Thermal noise, 1/f noise …
- Critical to ensure a perfect up-conversion (emission) and down-conversion (reception)
- Nonlinear operation (the oscillation frequency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

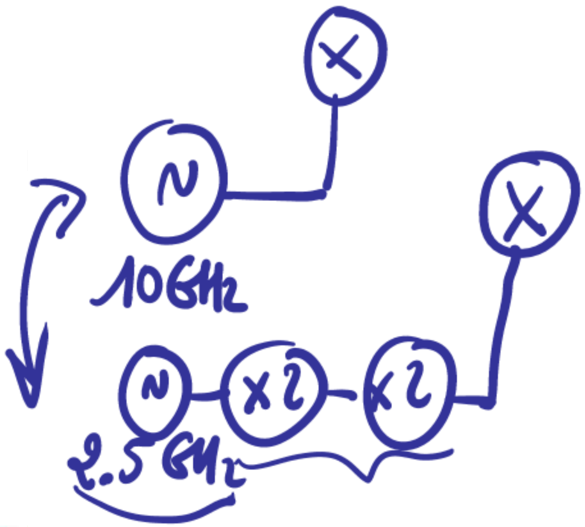


# Issue of 1/F noise of oscillators for ideal mixer operation

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



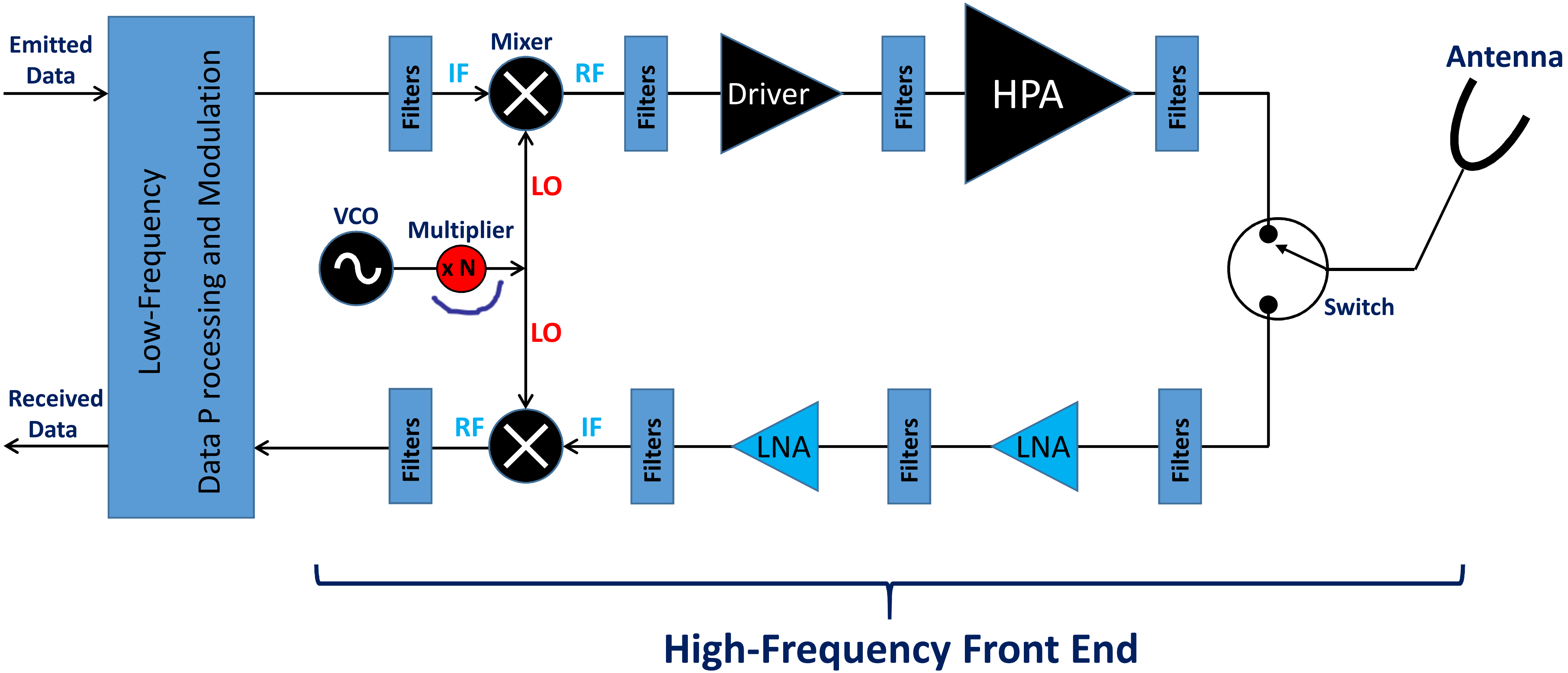





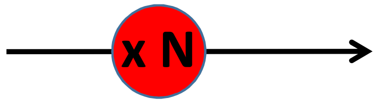
# III – High-Frequency Active Circuits in Communication Systems

## 2) Main High-Frequency Active Circuits

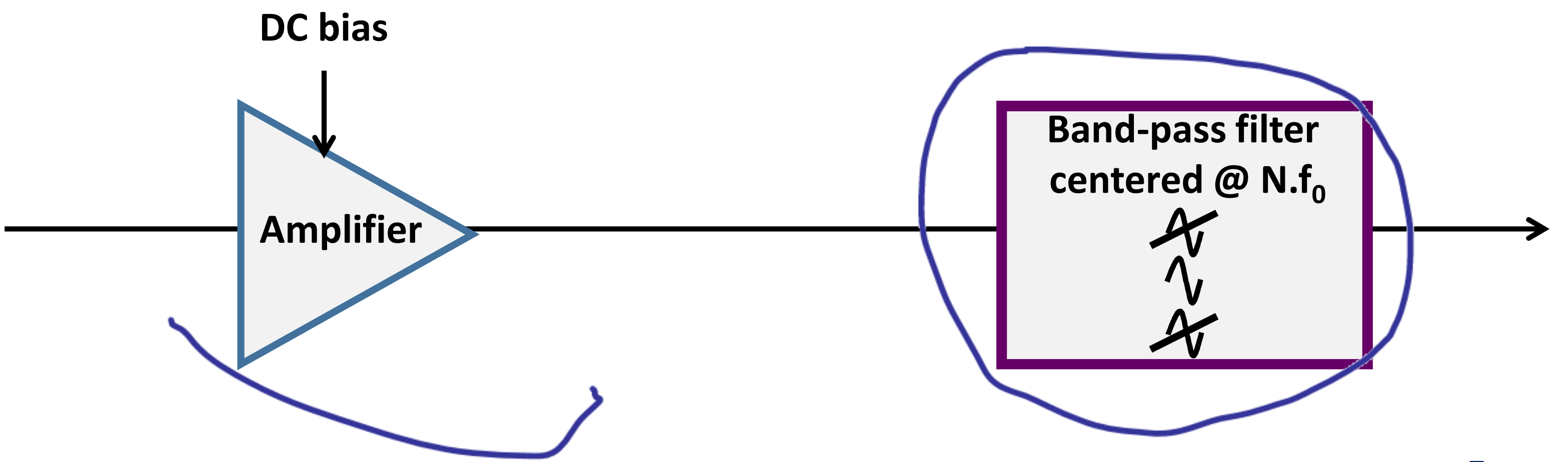
### d) **Multipliers**



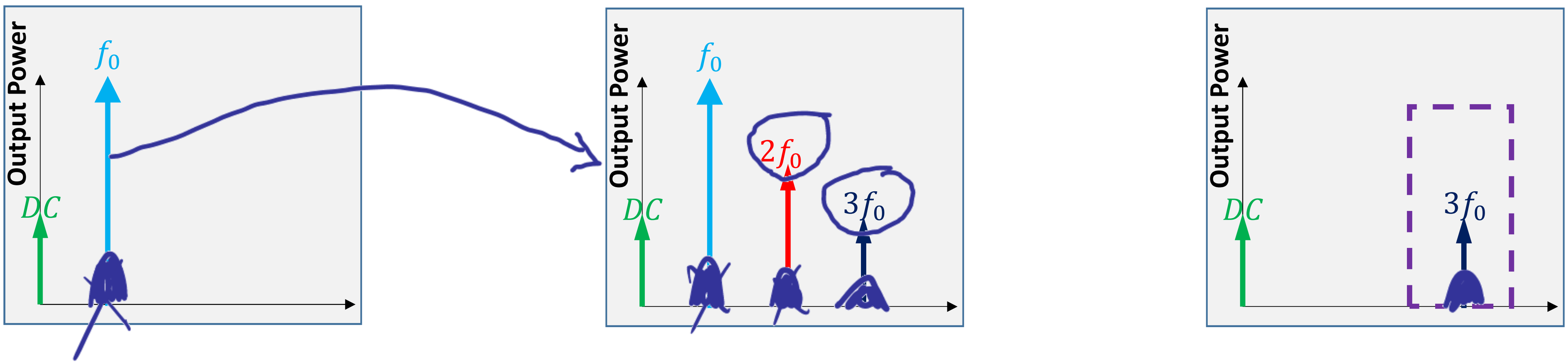
# Block diagram of a frequency multiplier




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



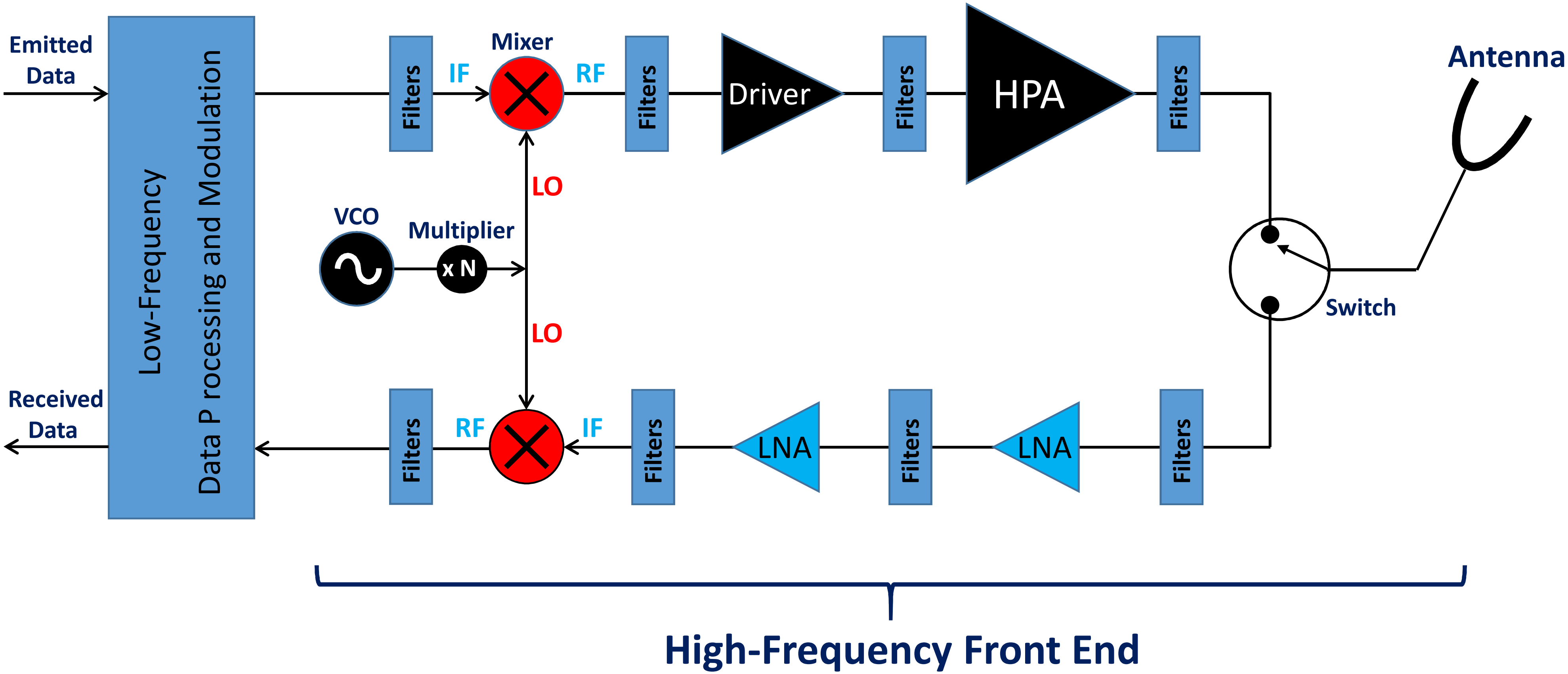

Example of tripler



# III – High-Frequency Active Circuits in Communication Systems

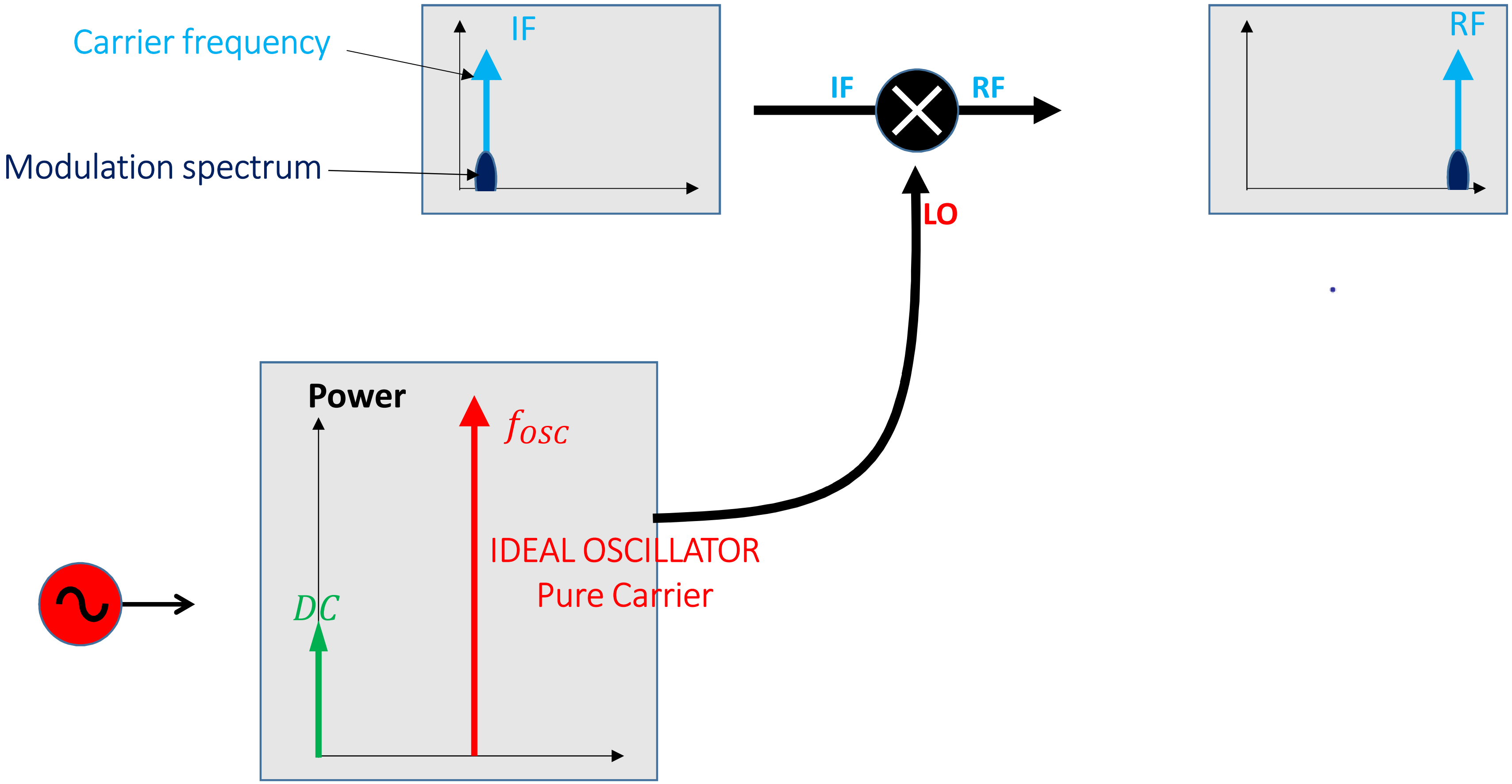
## 2) Main High-Frequency Active Circuits

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

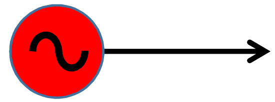


Issues of mixer designs (Conversion gain, Isolations…)

# Ideal Mixer



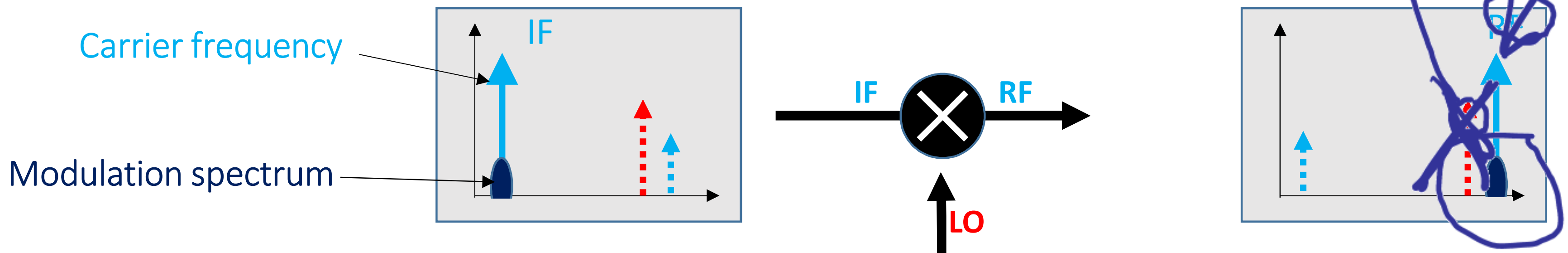
Issues of mixer designs (Conversion gain, Isolations…)



9.9GHz

10GHz

# Real Mixer



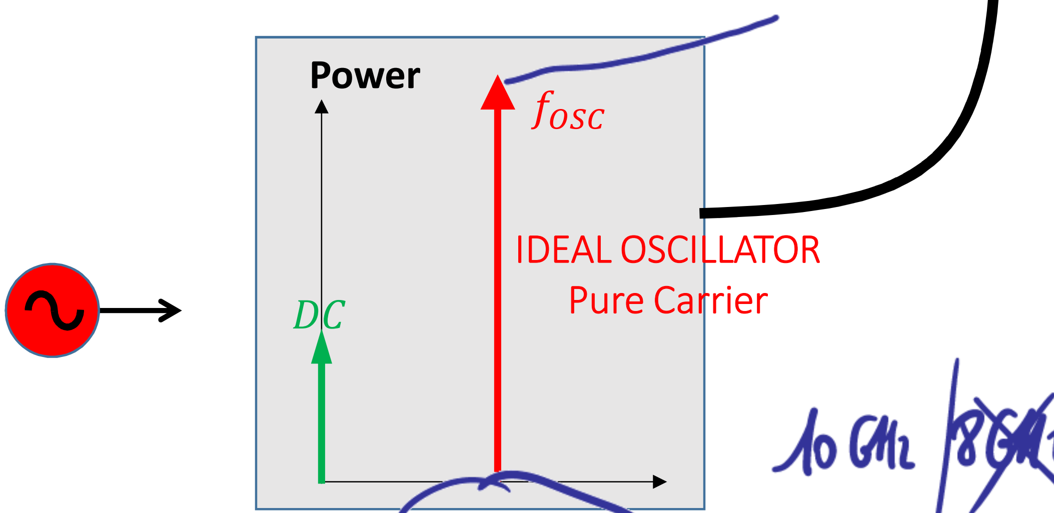

LO - RF isolation

$$f_{RF} = f_{osc} + f_{IF}$$

10GHz 9.9GHz

0,1 GHz

$$f_{RF} - f_{osc} = f_{IF}$$




10 GHz ~~8GHz~~

2G and 1.9G

100 MHz → 2GHz → 100 MHz → 10GHz

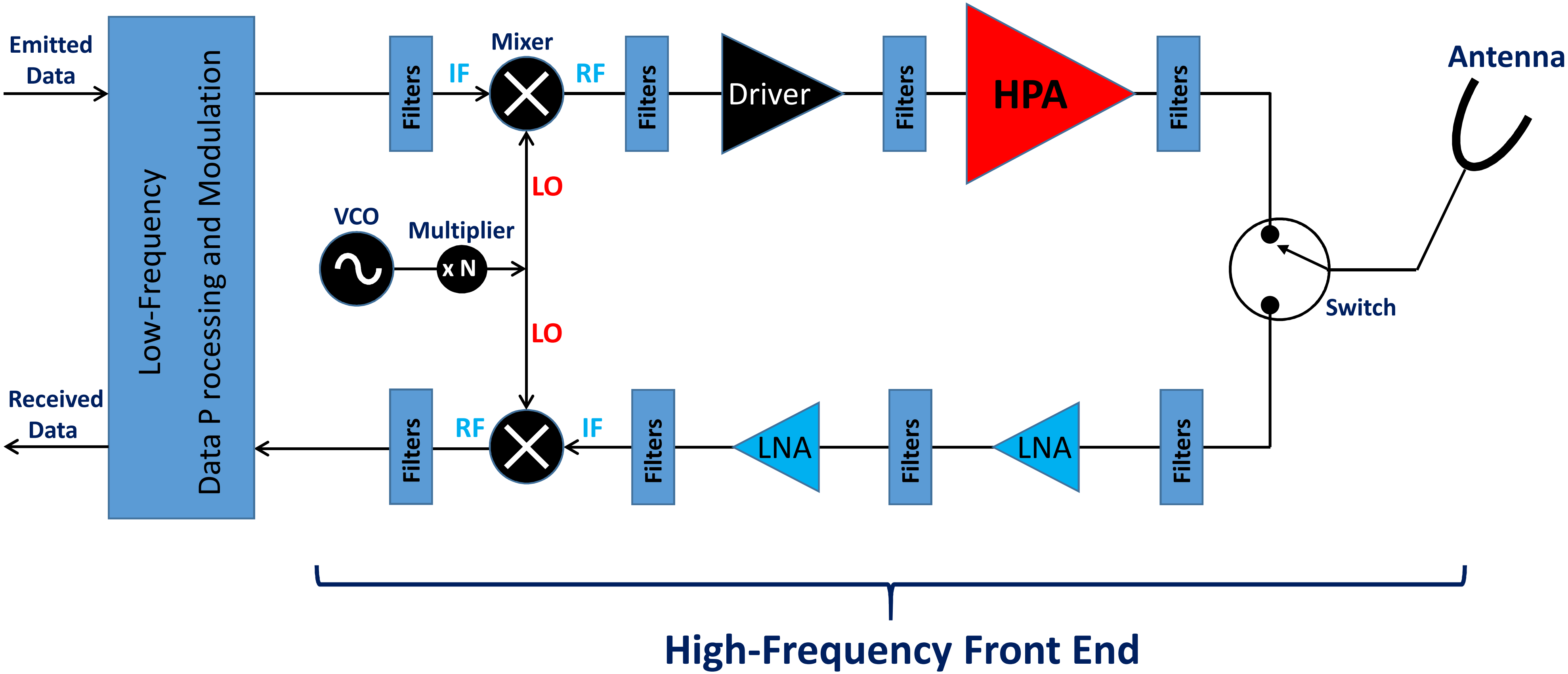
10GHz

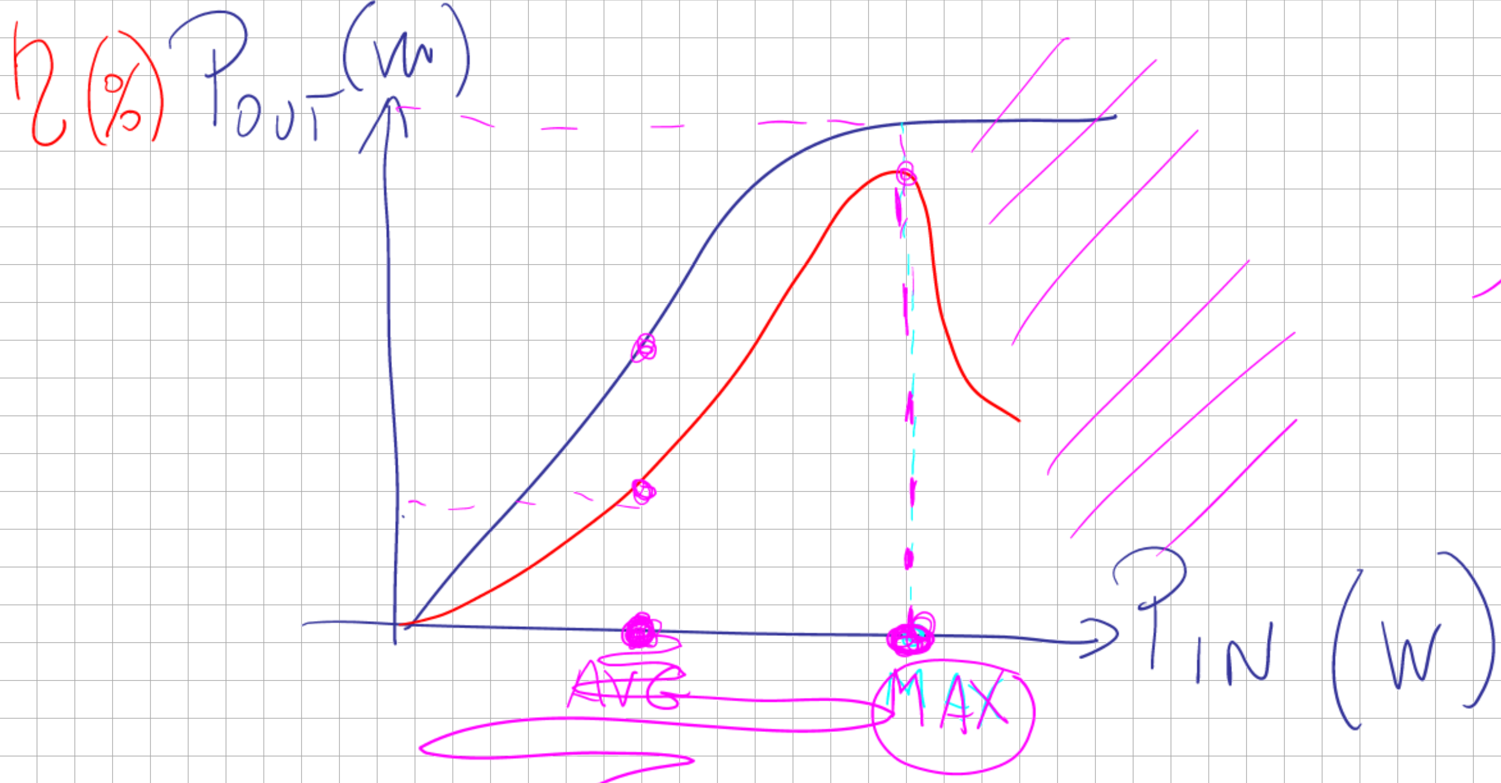
10GHz

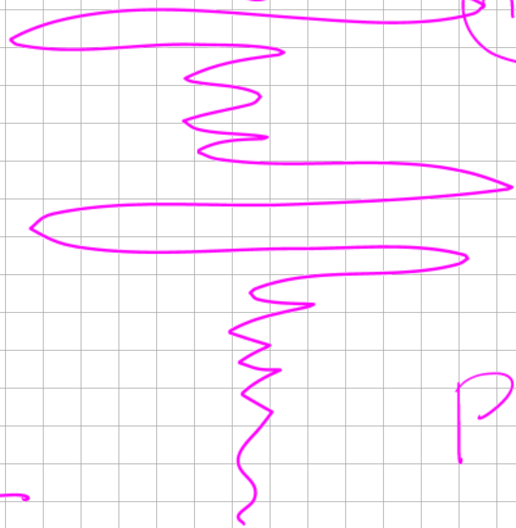
# III – High-Frequency Active Circuits in Communication Systems

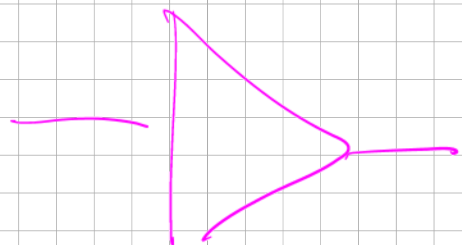
## 2) Main High-Frequency Active Circuits

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







QPSK

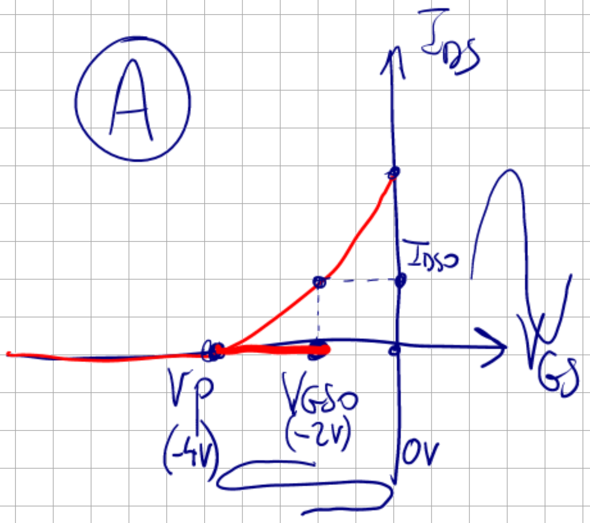
16QAM

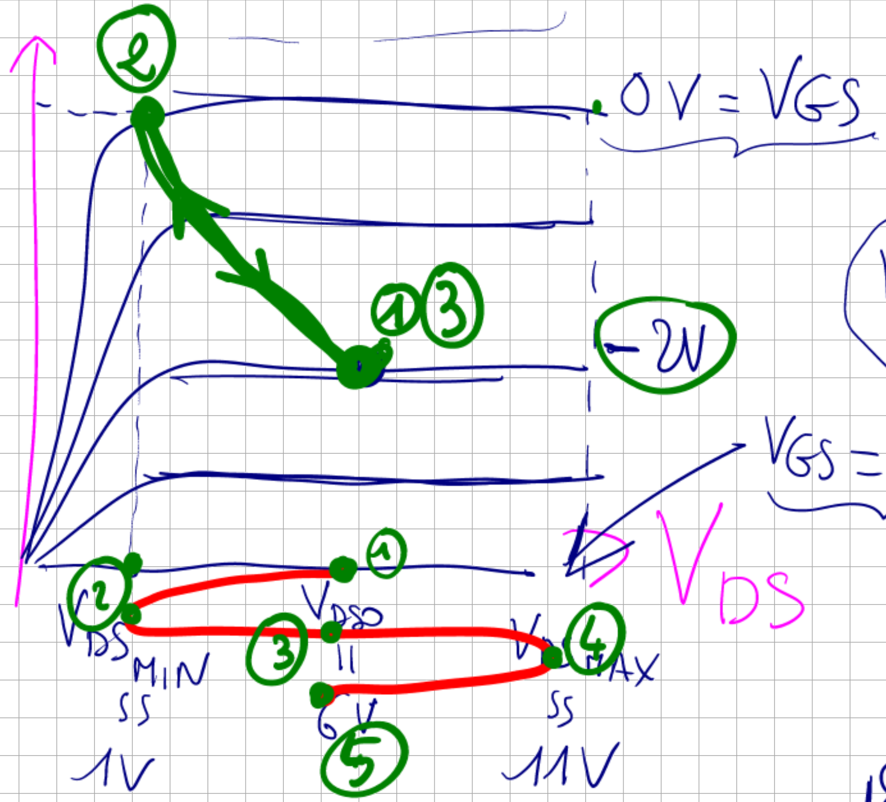
PAR

Peak to Average Ratio

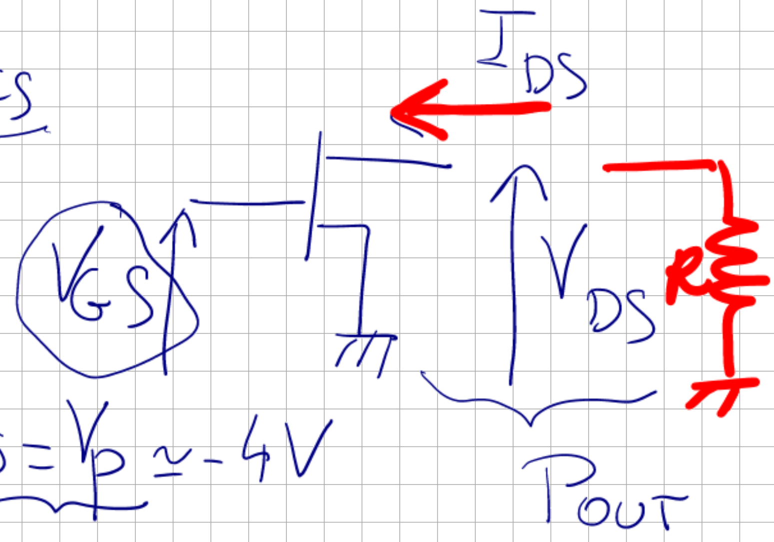
PAR ↑

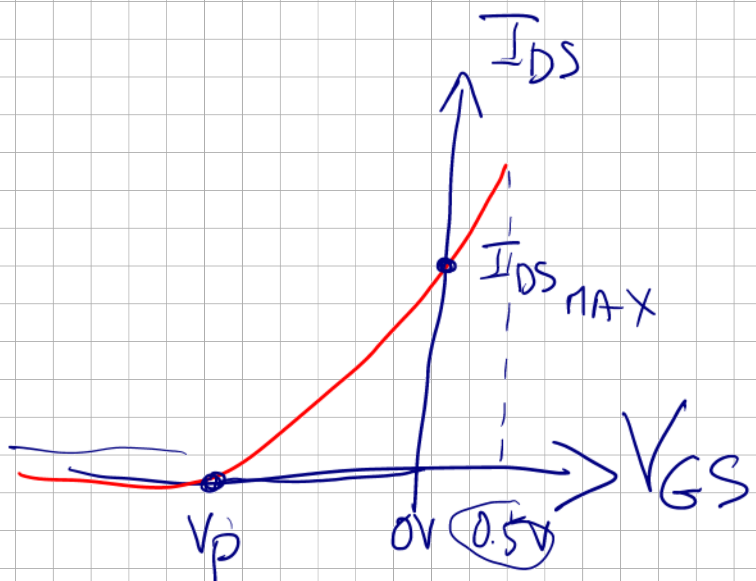
I-V characteristic

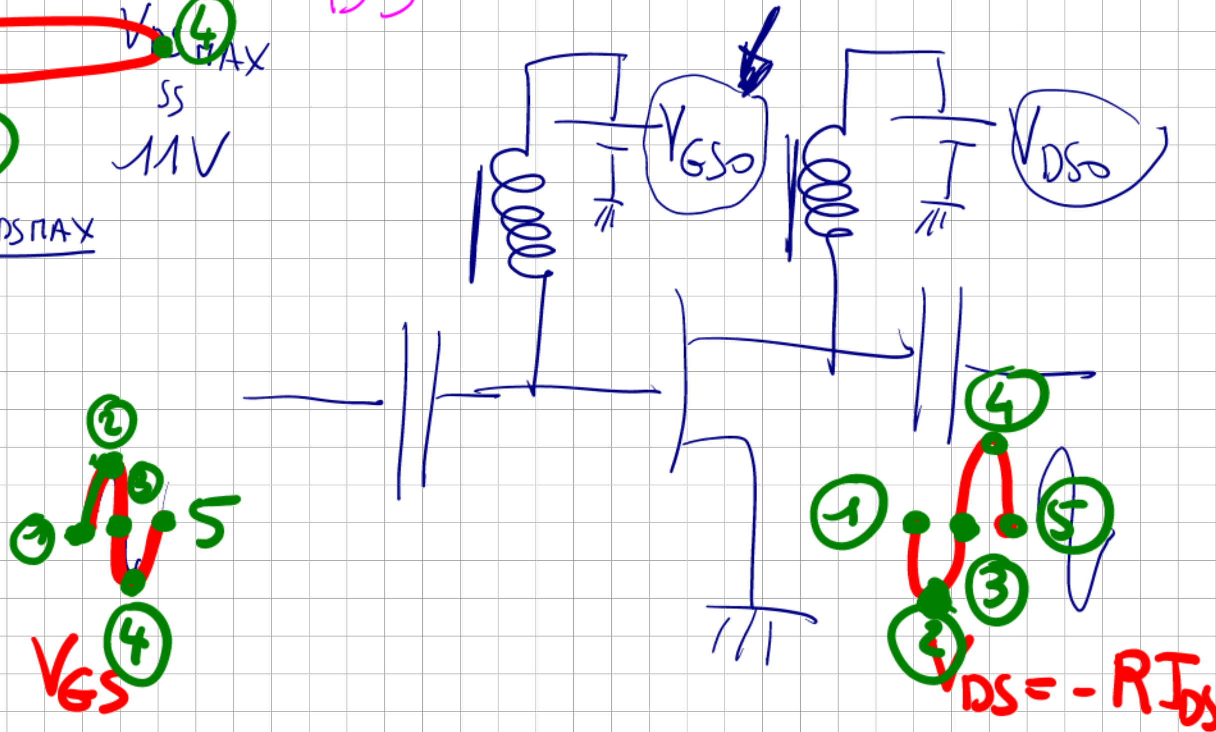


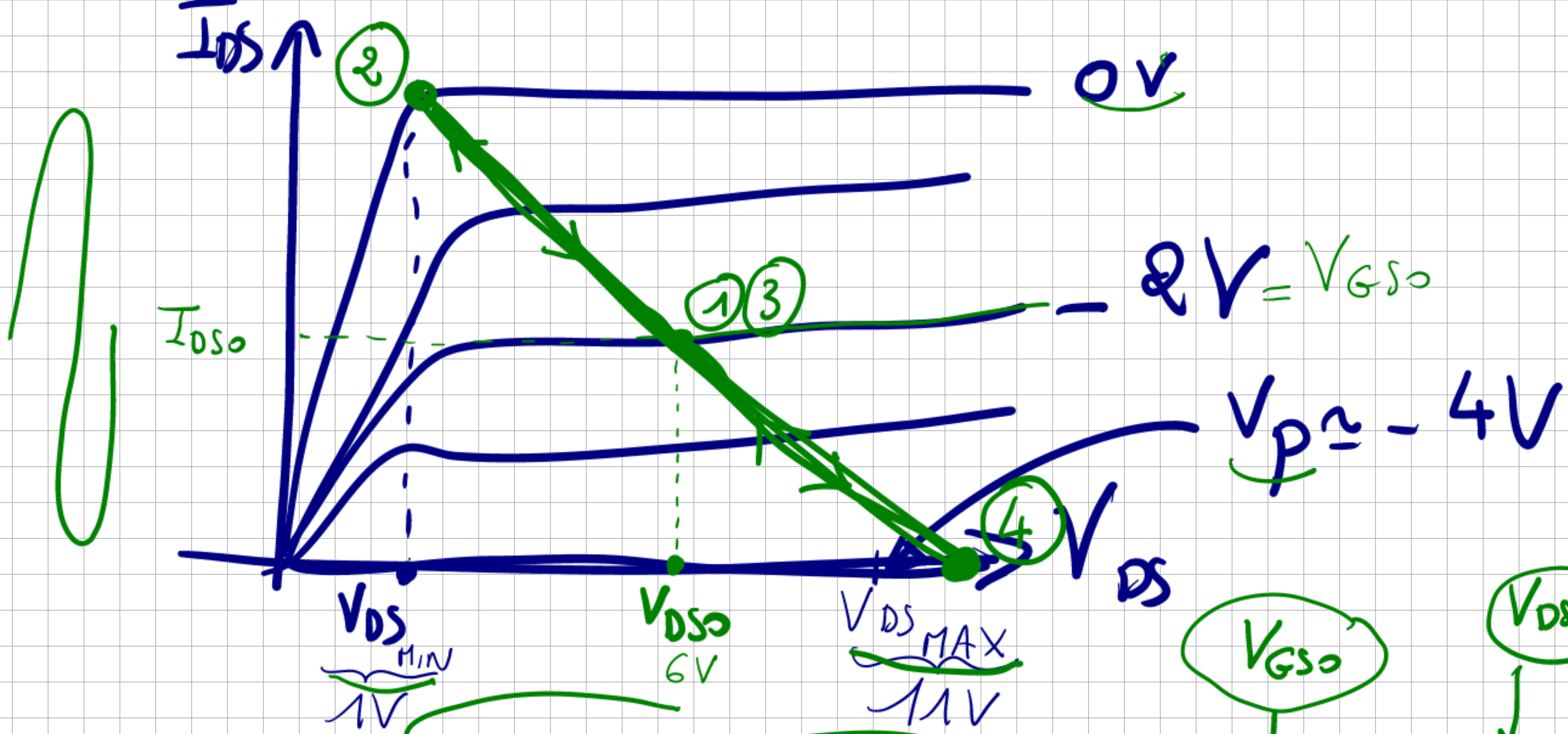

$$V_{DS0} = \frac{V_{DSMIN} + V_{DSMAX}}{2}$$

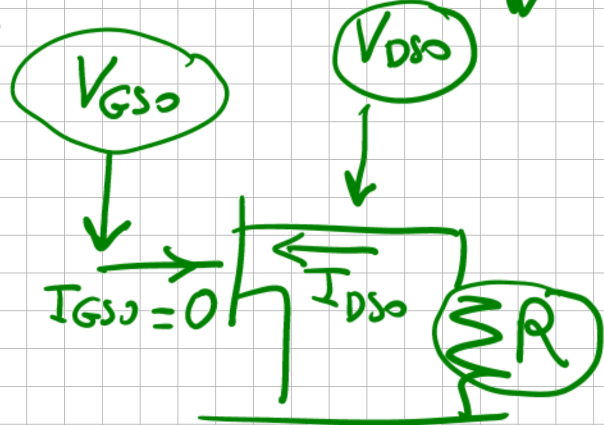


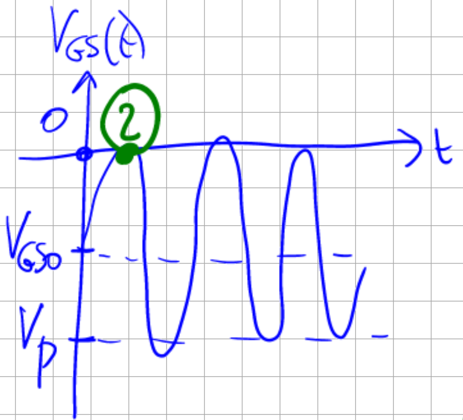



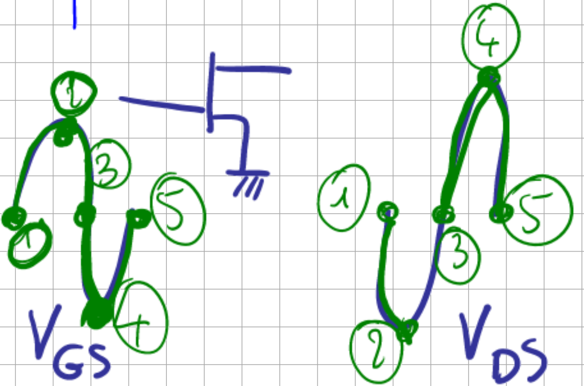



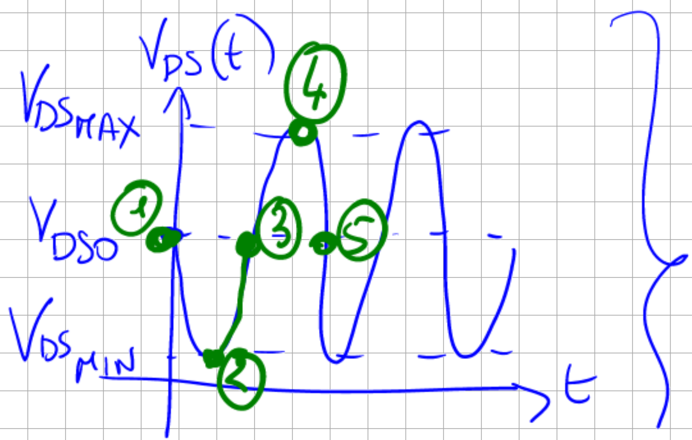
# Load-Line




## Class A

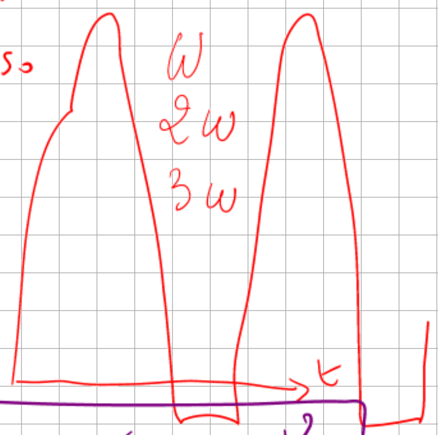
- Pout max
- Linear
- Poor Efficiency

$\eta_{MAX_A} = 50\%$

$$P_{DC_A} = V_{DSo} \times I_{DSo}$$

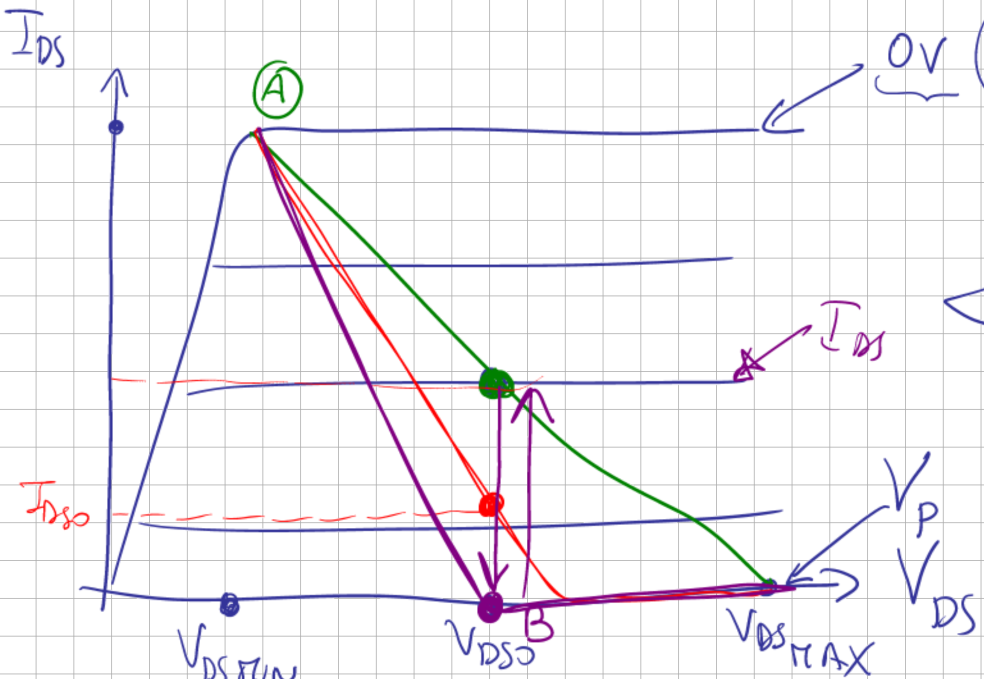
$$\eta \approx \frac{P_{OUT}(\omega)}{P_{DC}}$$

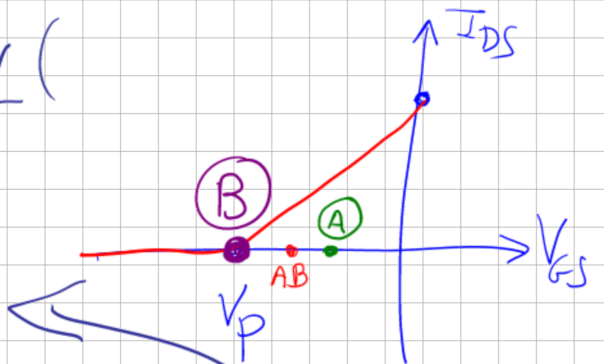
$$P_{DC} = V_{DS0}\, I_{DS0}$$



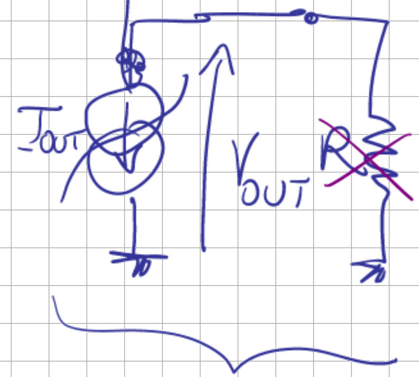

$$\boxed{I_{DS}(t) = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2}$$

$$V_{DS0} = \frac{V_{DSMIN} + V_{DSMAX}}{2}$$







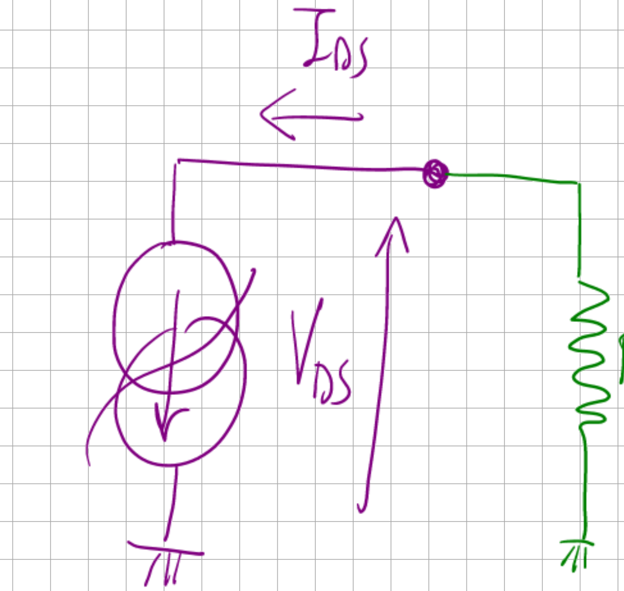

$$V_{OUT} = |V_{OUT}|\, e^{j\arg(V_{OUT})}$$

$$P_{OUT}(\omega) \approx \frac{1}{2} \mathrm{Re}\big(\underbrace{V_{OUT} \times I_{OUT}^{*}}\big) = \frac{1}{2} \underbrace{|V_{OUT}|}_{\text{swings}} |I_{OUT}| \underbrace{\cos\left(\varphi_{V_{OUT}} - \varphi_{I_{OUT}}\right)}_{\to 1}$$

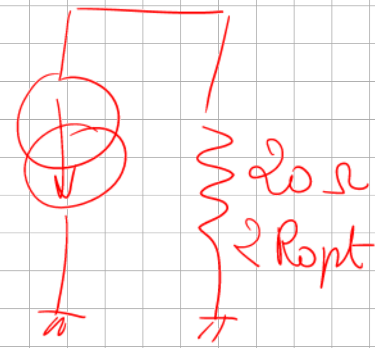
AB class
B class

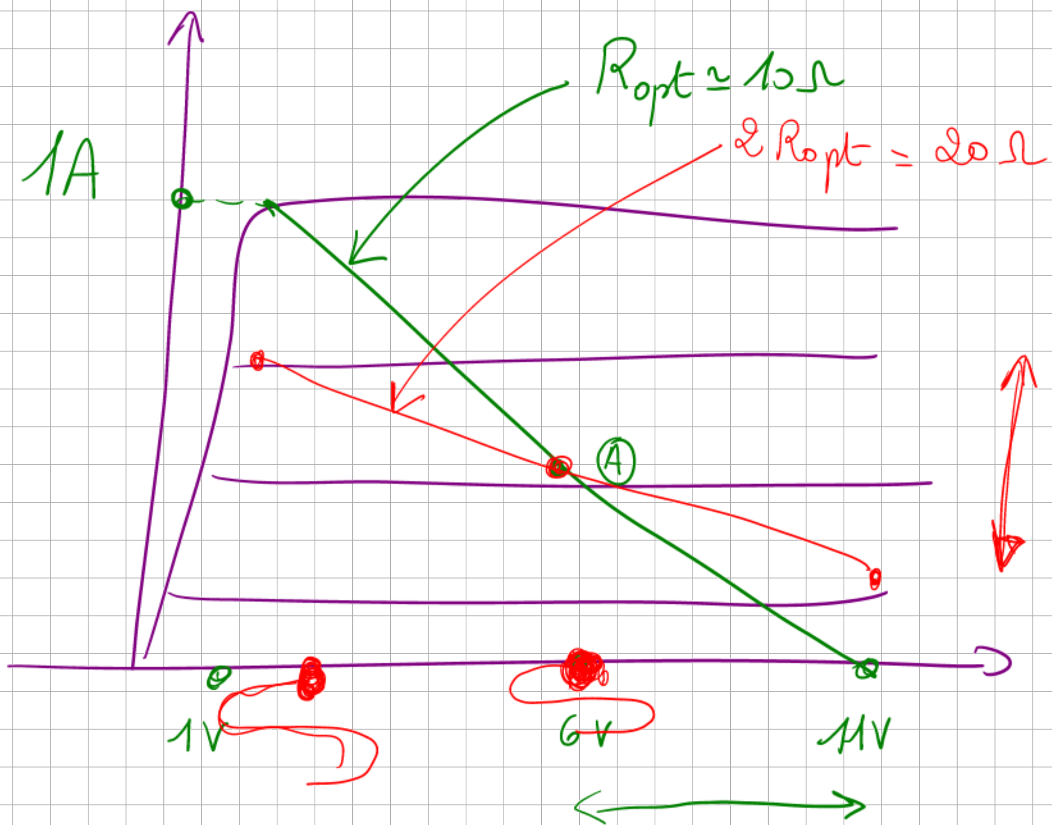
$P_{DC} \downarrow \to 60\%$

$I_{DS0} \downarrow$

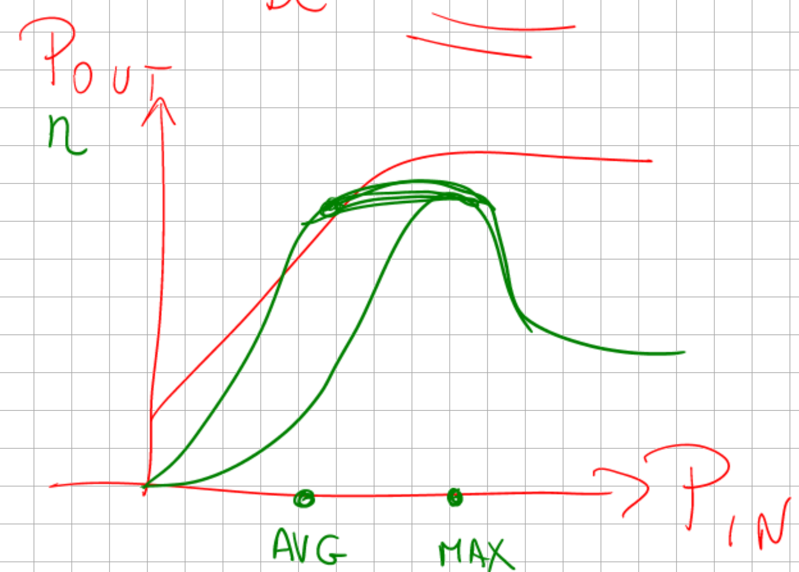



$$R_{opt} = \frac{|V_{DS}|_{max}}{|I_{DS}|_{max}} = \frac{5V}{0.5A} = 10\Omega$$




$$P_{DC} = V_{DS0} I_{DS0}$$



# 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)

- DOHERTY

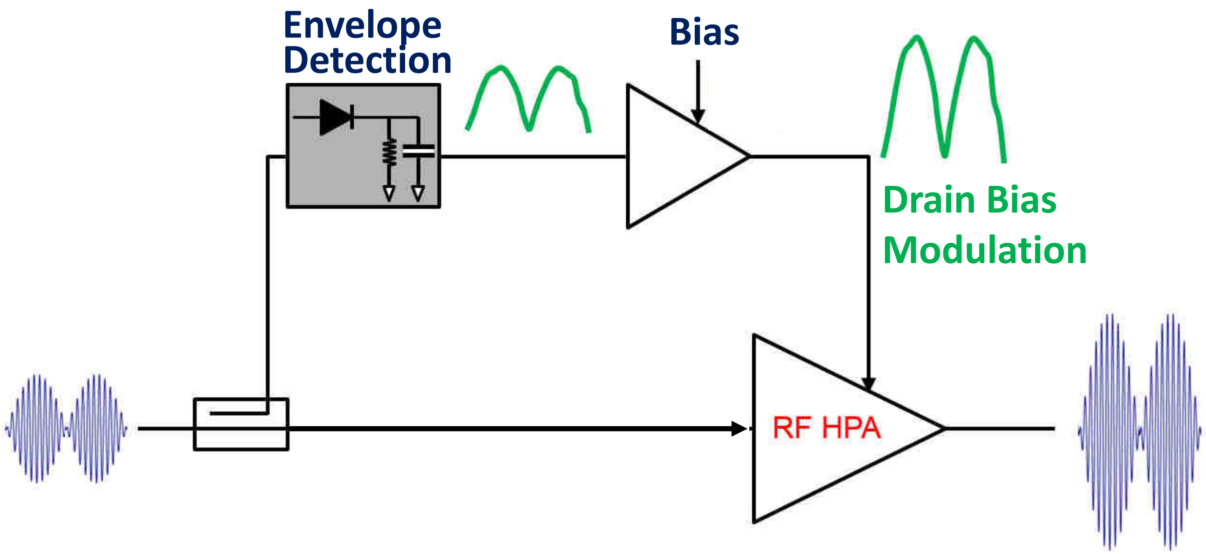
- LINC (Linear amplification with Nonlinear Components)

# 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**



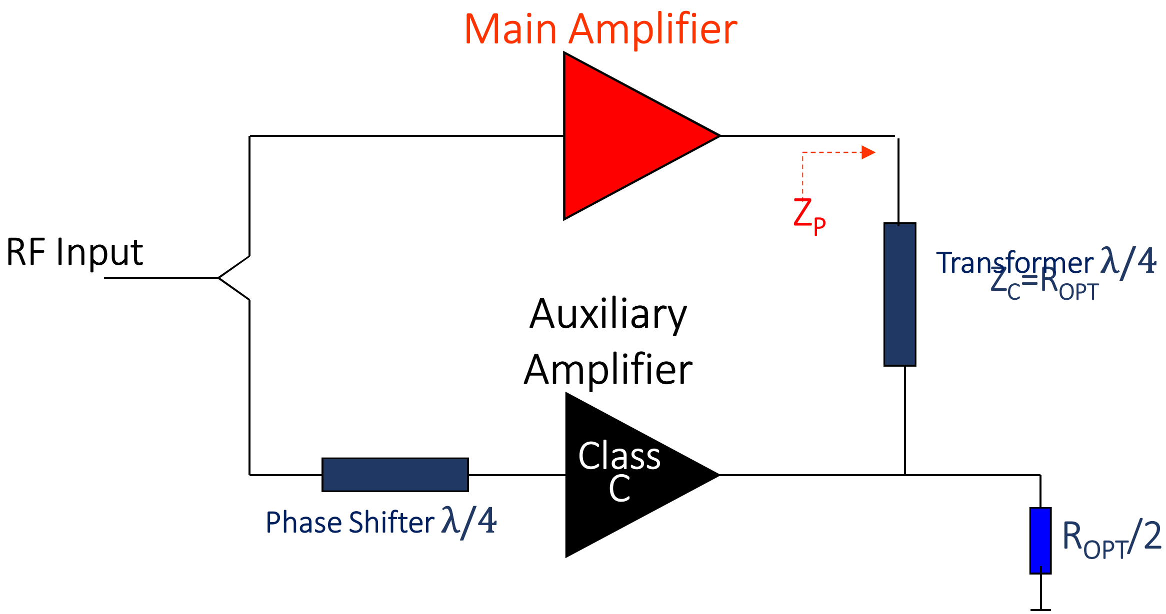
# III – High-Frequency Active Circuits in Communication Systems

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**



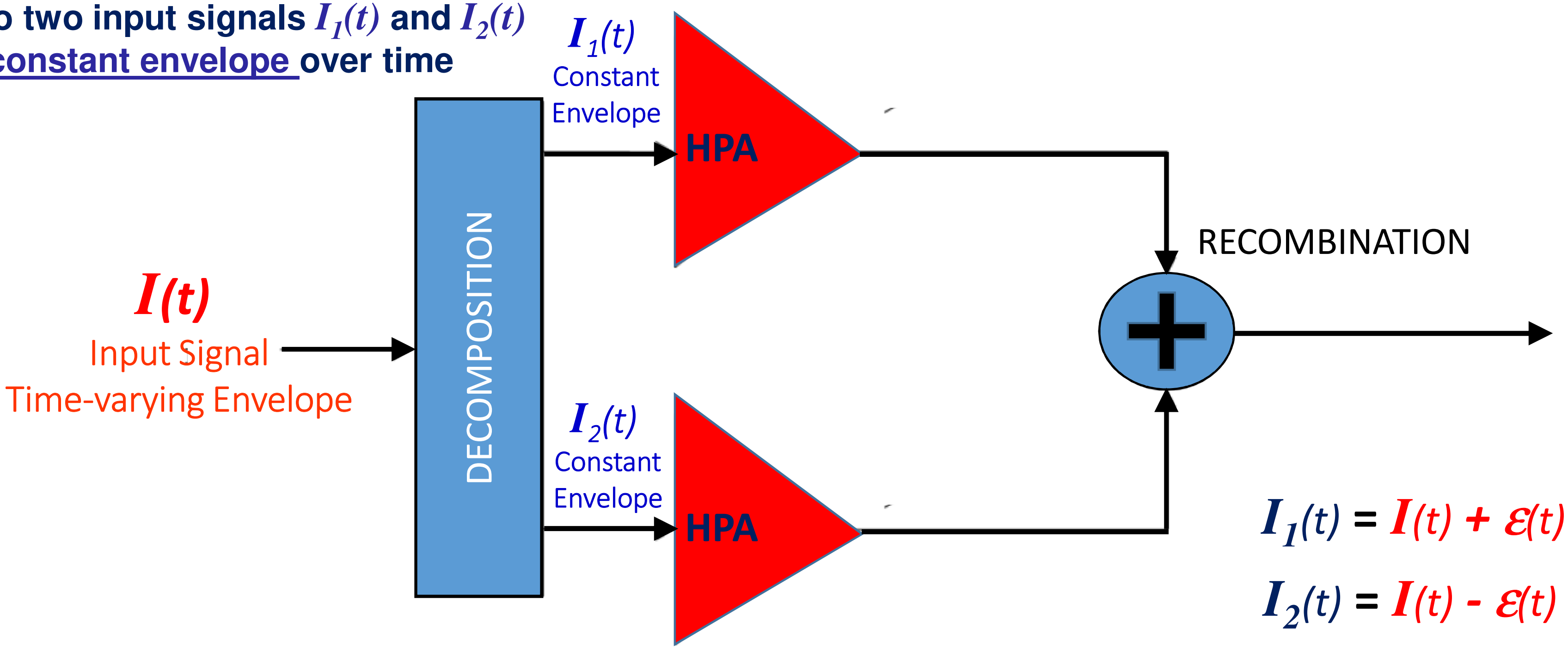
# III – High-Frequency Active Circuits in Communication Systems

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** $R_{TH}$ **($\Omega$)** |
| **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)