HPA

(High Power Amplifiers)

Basics of Active and Nonlinear High-Frequency Electronics

Nonlinear electrical modeling of transistors for CAD

ADS

Michel CAMPOVECCHIO

$f > 1\,GHz$

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

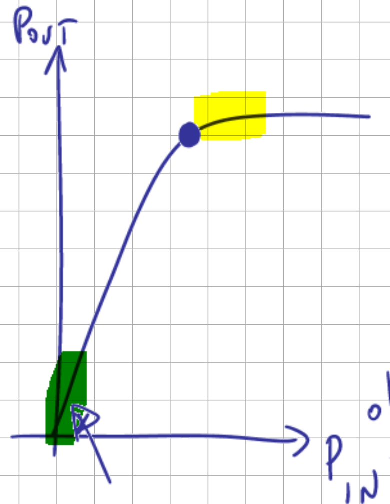
Part I : Michel Campovecchio (michel.campovecchio@unilim.fr)
- Lectures : 12 H - Tutorials : 15 H → Lectures and Tutorials 27 H

Part II : Jean Michel Nebus (jean-michel.nebus@unilim.fr)
- Lectures : 12 H - Tutorials : 15 H → Lectures and Tutorials 27 H

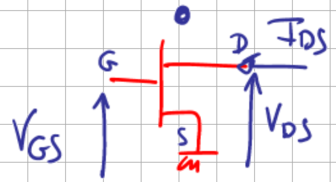
- Chapter I : Introduction to active high-frequency circuits in communication systems
- Chapter II : Introduction to the Non-linear Electrical Modeling of microwave transistors
- Chapter III : Design method of narrow-band power amplifiers
- Chapter IV : Architectures of high-frequency mixers
- Chapter V : Architectures of 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)

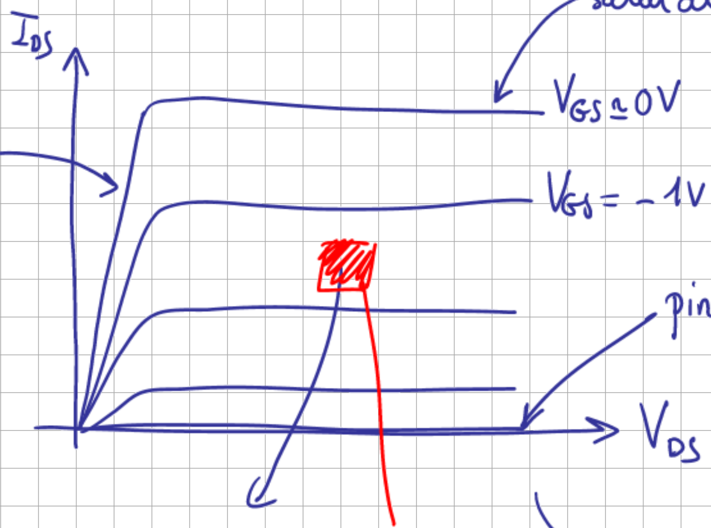
HEMT (High Electron Mobility Transistors)



ohmic region

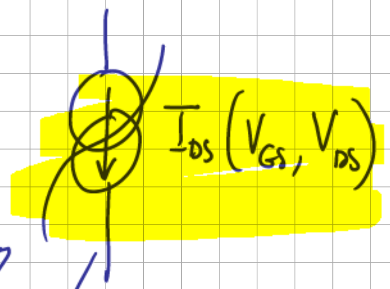


saturated region



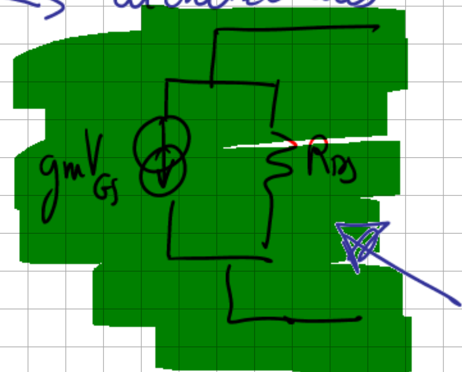
pinch-off voltage V_p

$I_{DS}(t) =$



study analytically simple circuits

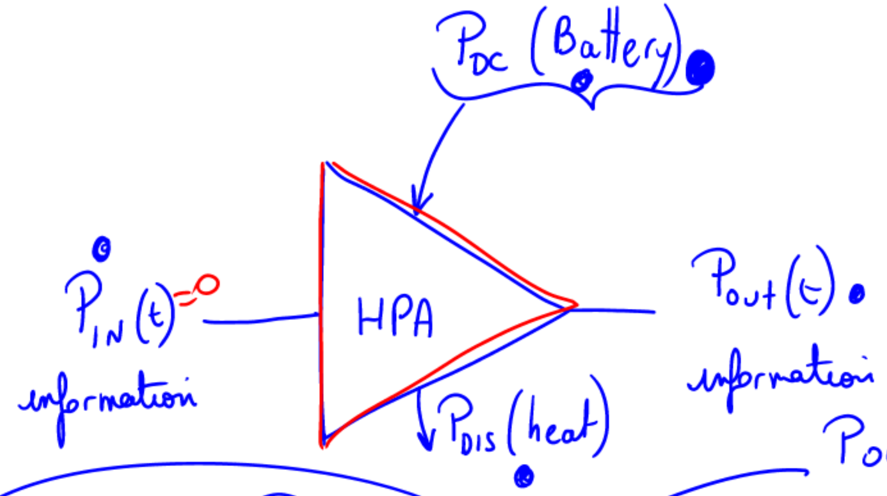
architectures



Bias

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

Erasmus+



Chapter I :

Introduction to active high-frequency circuits in communications systems

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

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

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

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

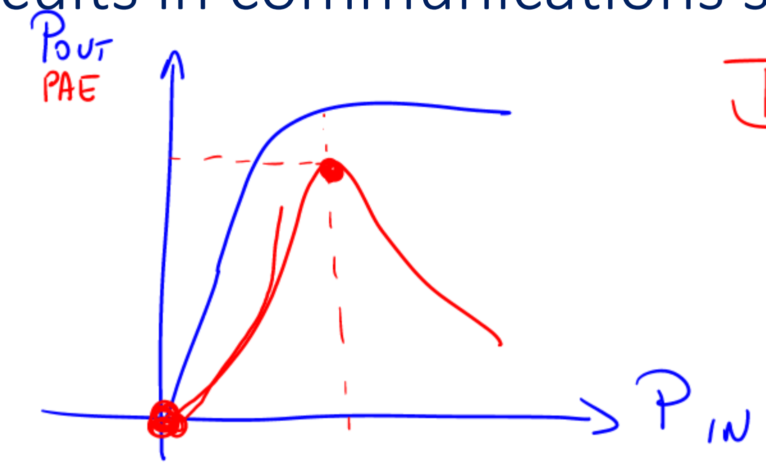
$$P_{DIS} = P_{DC}(1 - PAE)$$

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

Power Added Efficiency

$$0 < PAE < 1$$

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

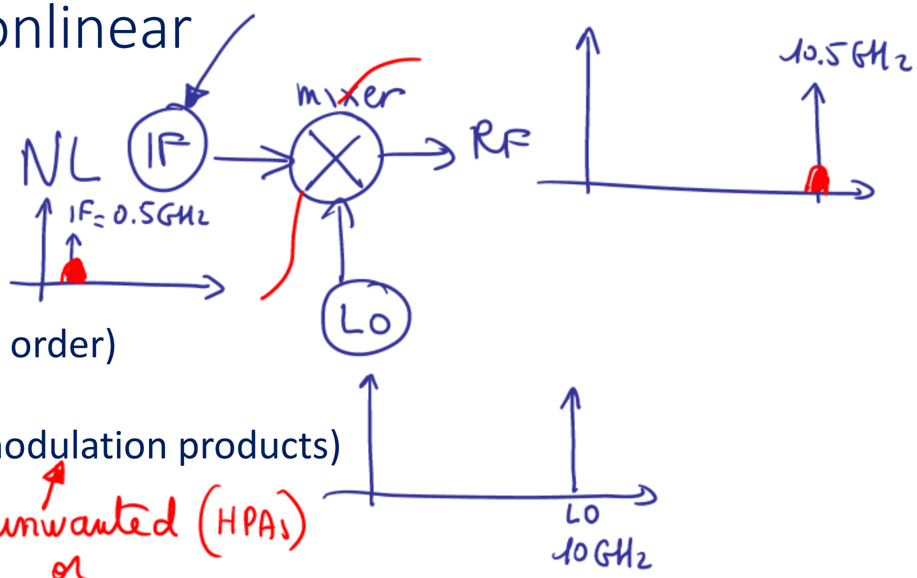


I - Differences Active/Passive & Linear/Nonlinear

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)

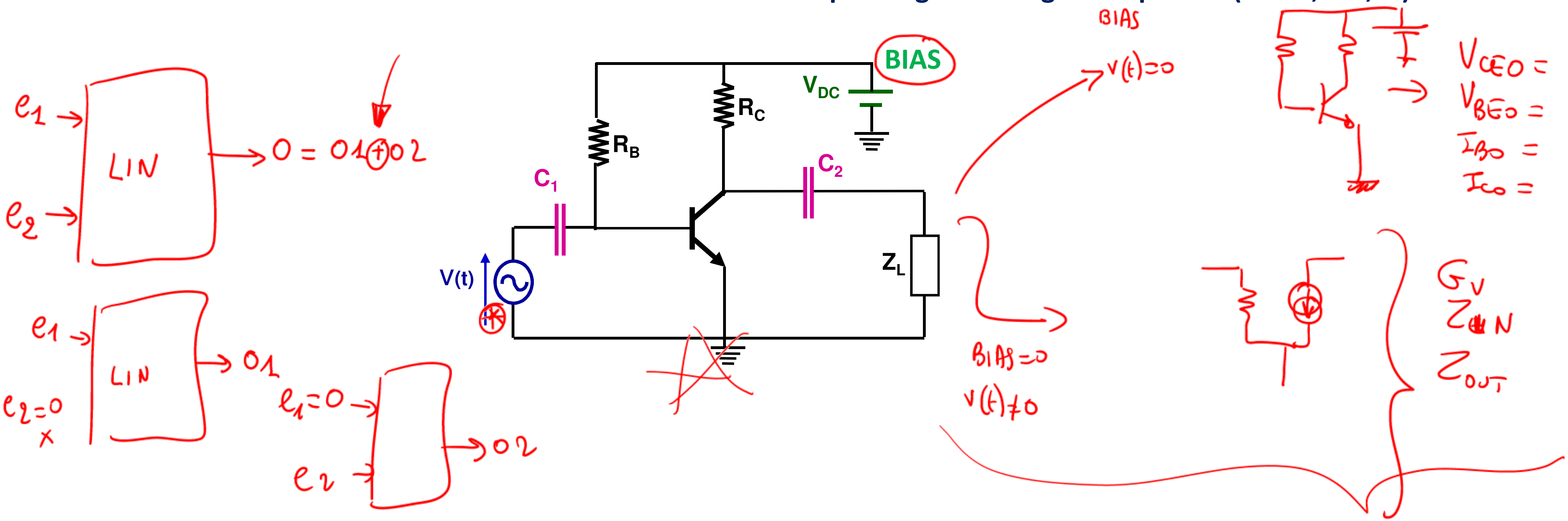


unwanted (HPAs)
or
wanted (mixers)

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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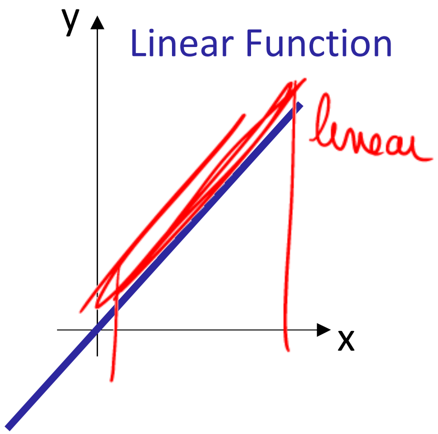

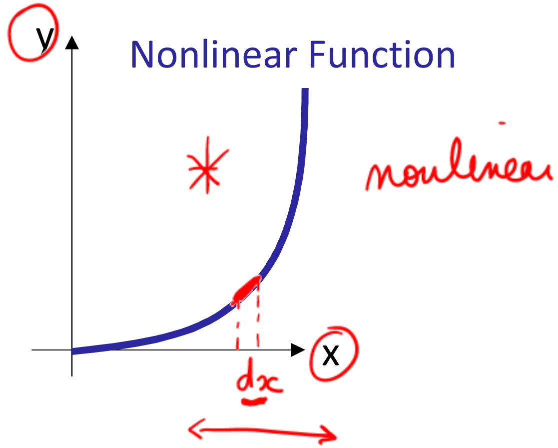

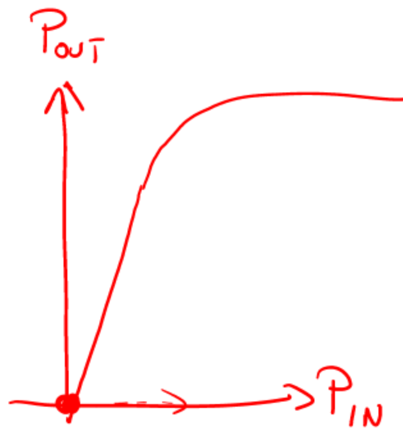

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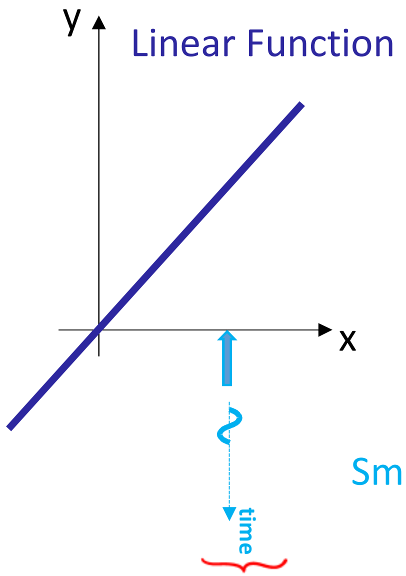
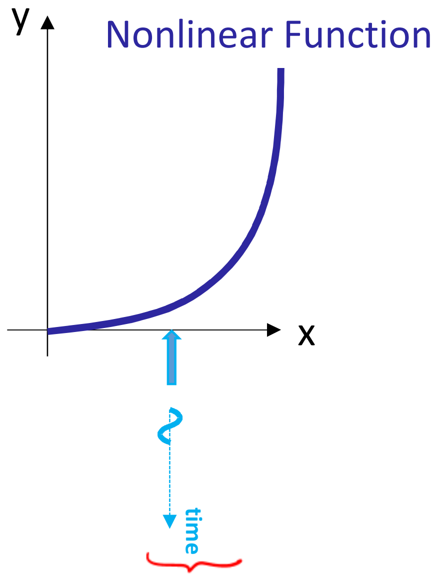


Applied
Small Sinusoidal Signal



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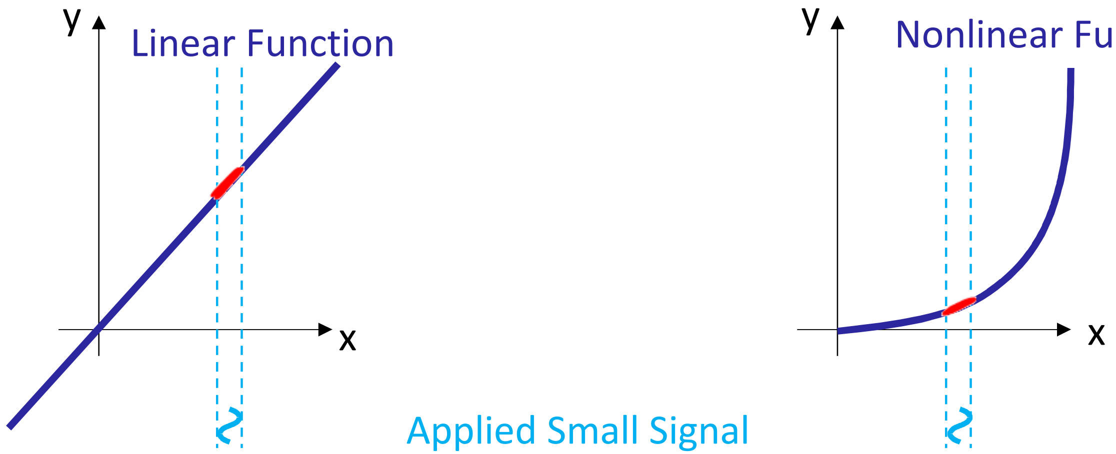

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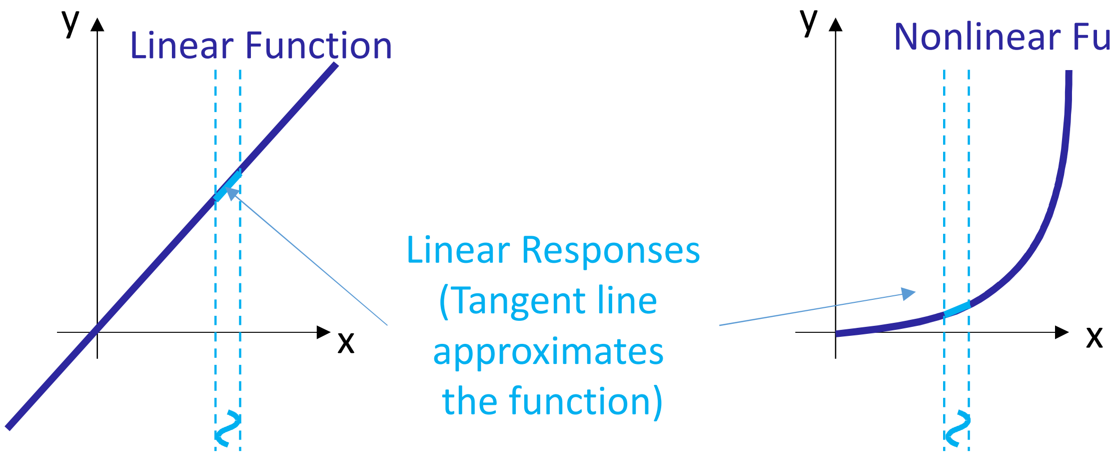

Linear and Nonlinear circuits give a linear response to small signals

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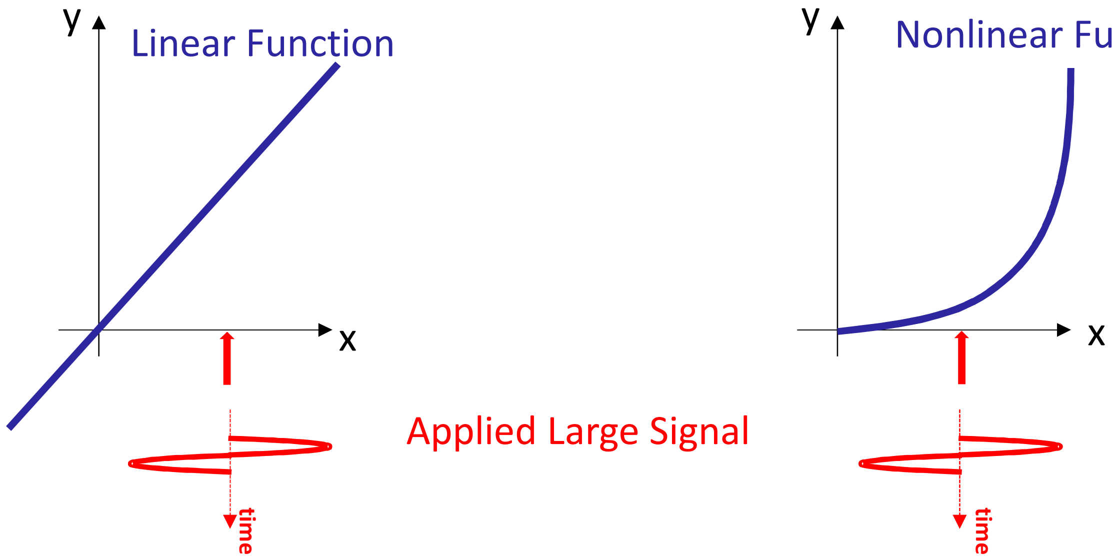

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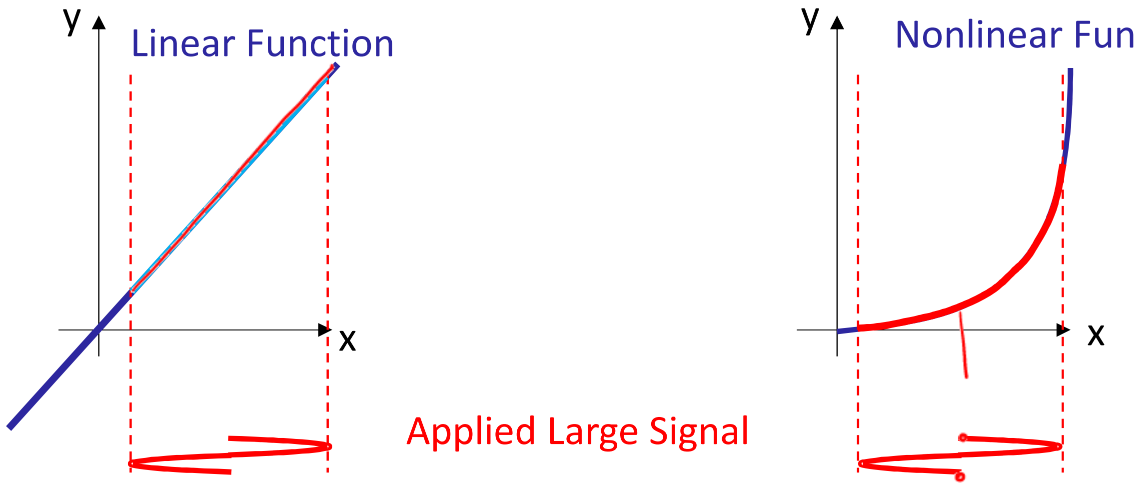

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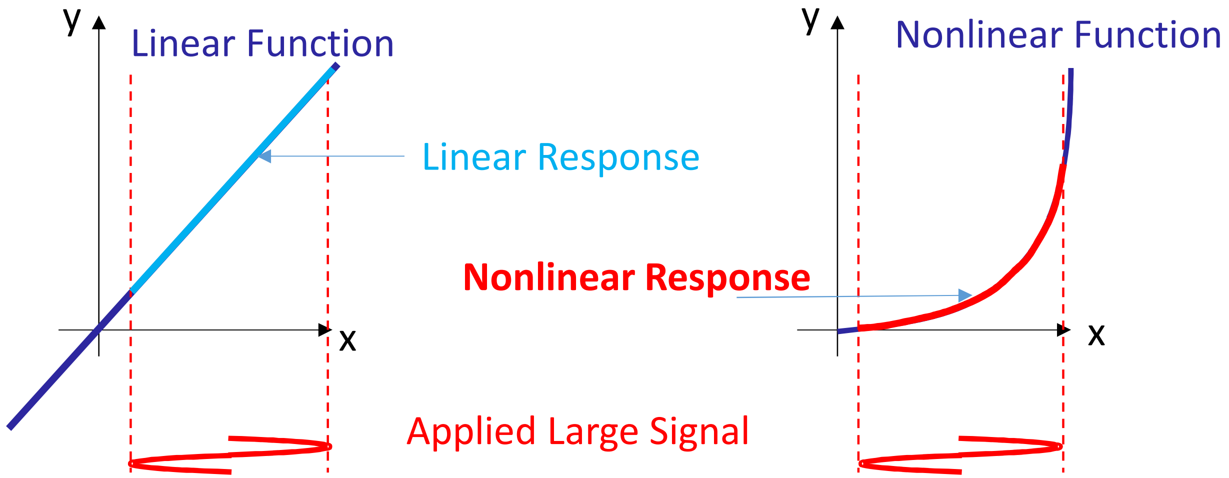


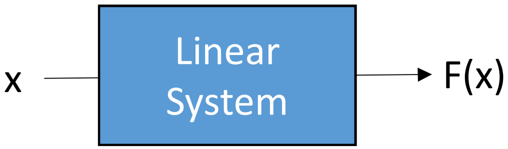
Linear circuits remain linear in the case of large signals

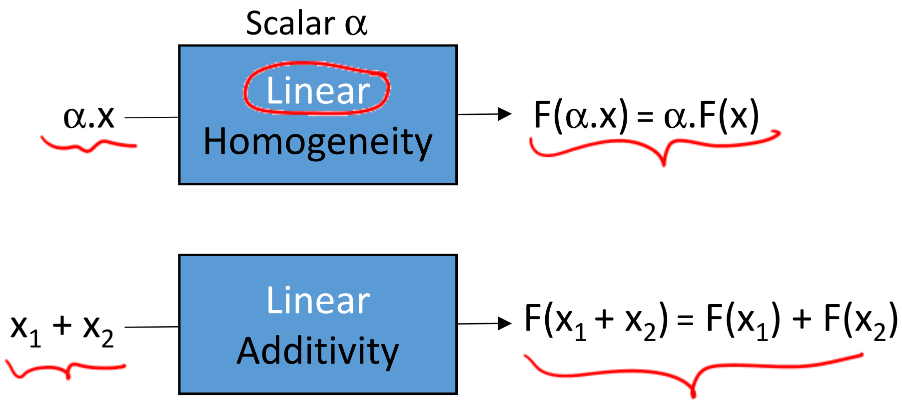
Nonlinear circuits give nonlinear responses to large signals → Harmonic generation in frequency domain

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**



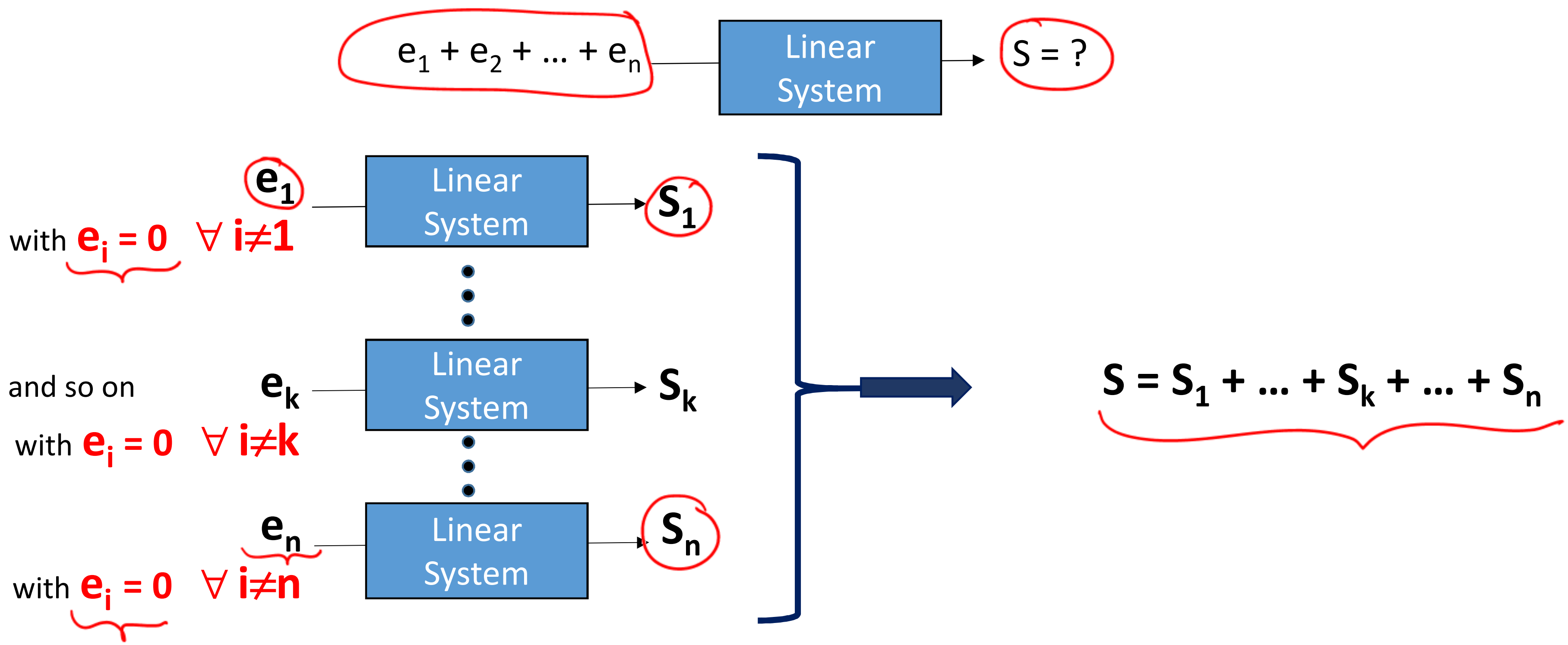


I - Differences Active/Passive & Linear/Nonlinear

2) Linearity (superposition principle)

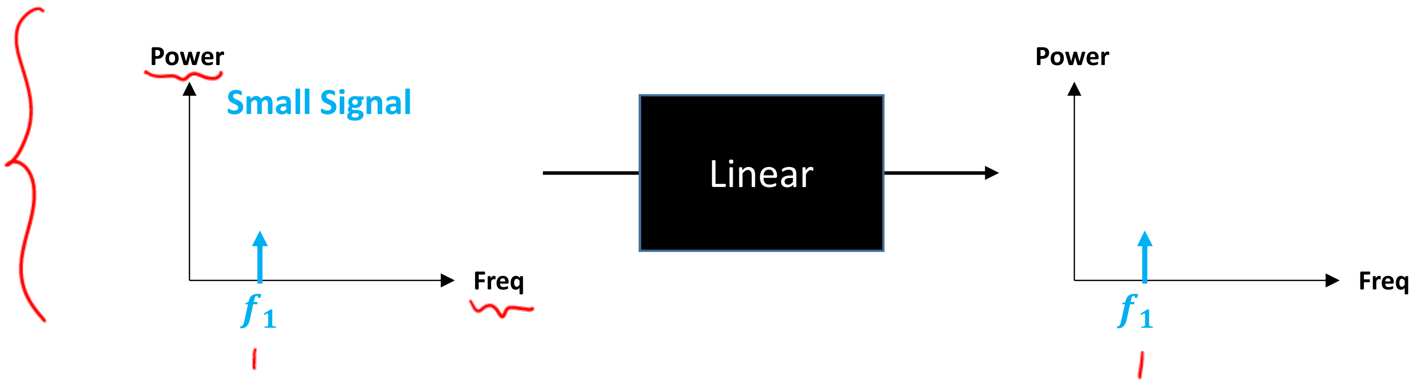
In the case of electrical circuits, the **superposition theorem** states that :

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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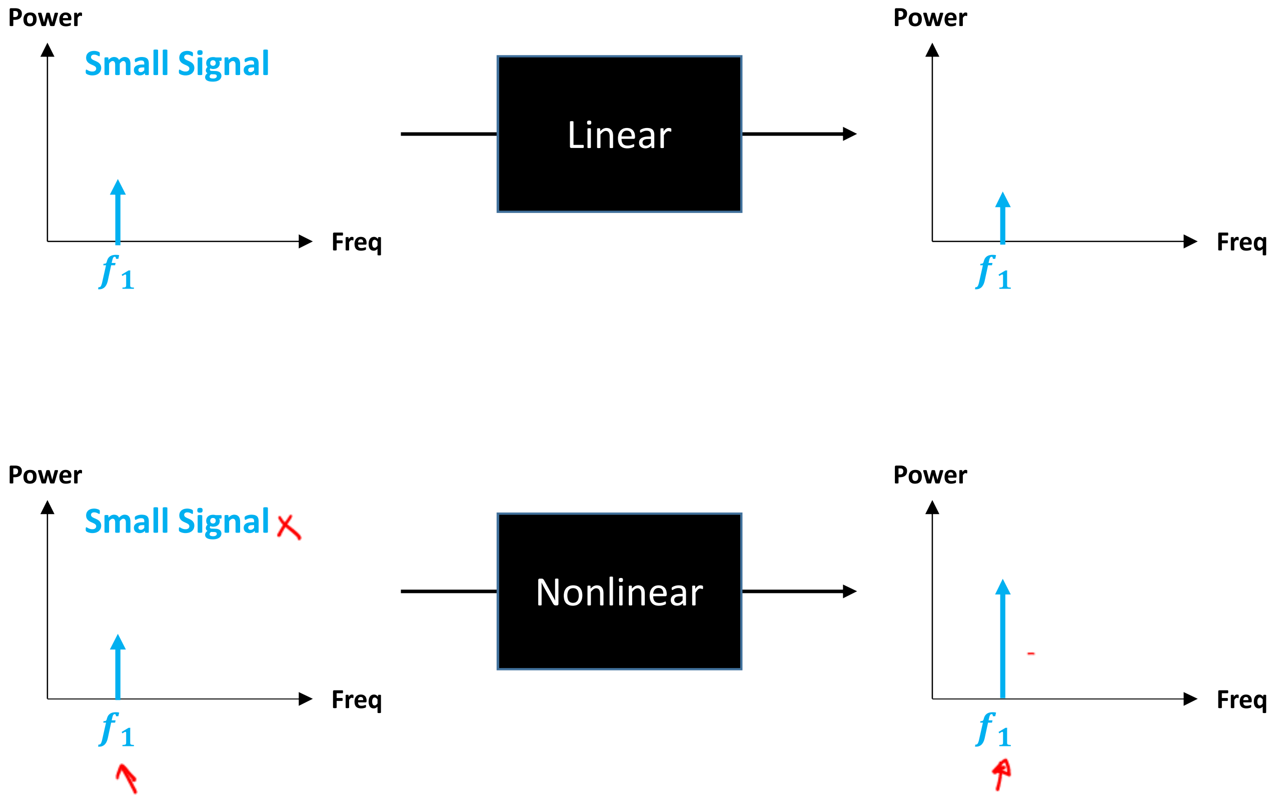
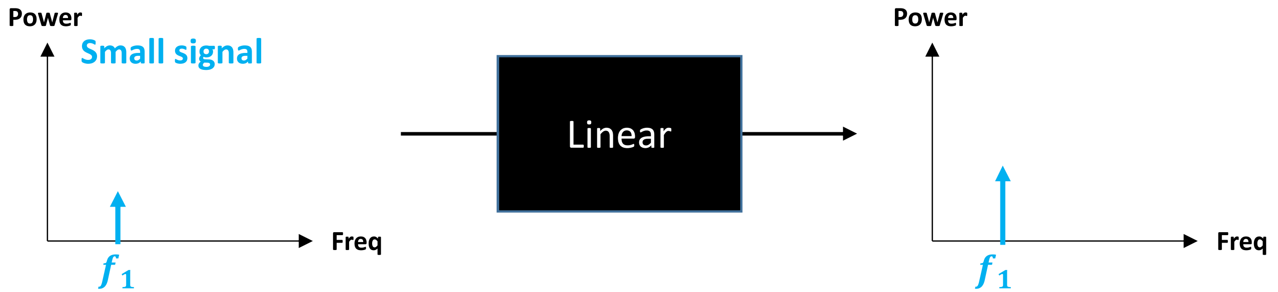


Whatever the type of device (linear or nonlinear), its response to small signals remains linear

I - Differences Active/Passive & Linear/Nonlinear

2) Linearity / Non Linearity (single carrier)



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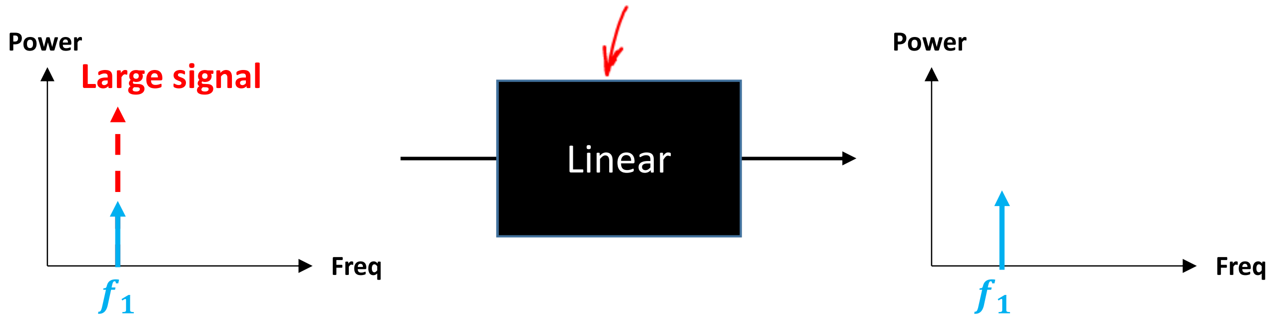

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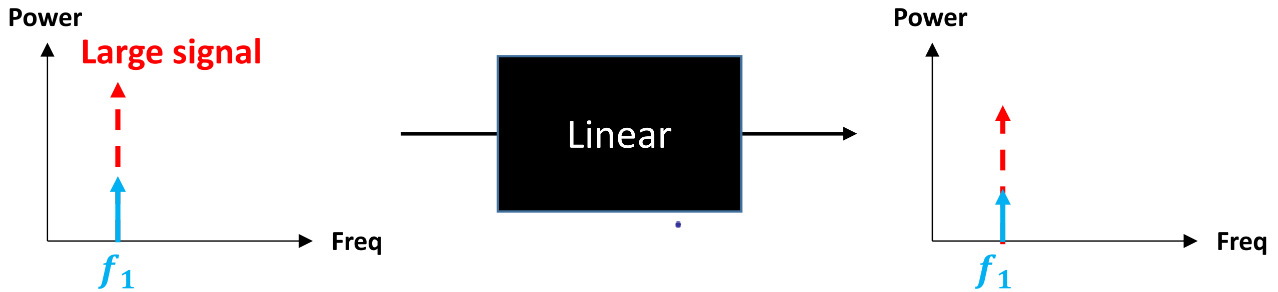

The response remains linear

I - Differences Active/Passive & Linear/Nonlinear

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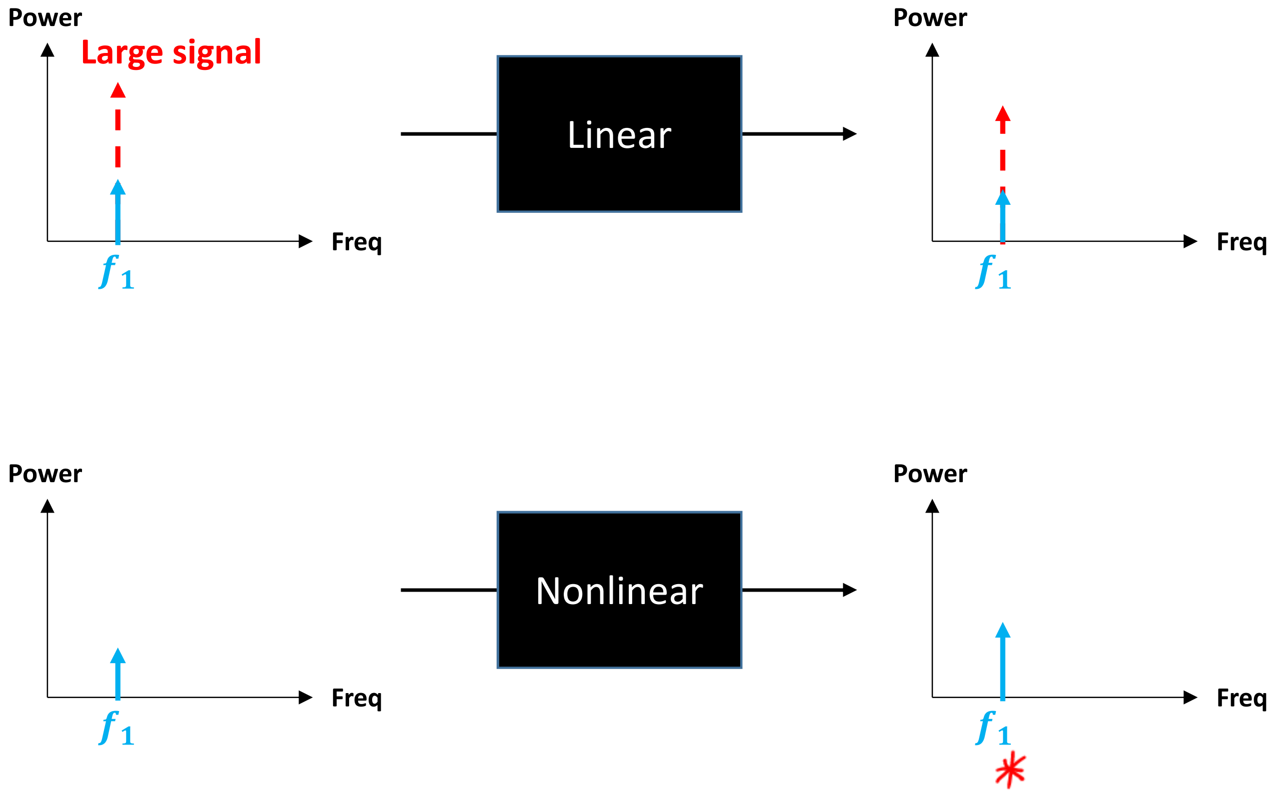

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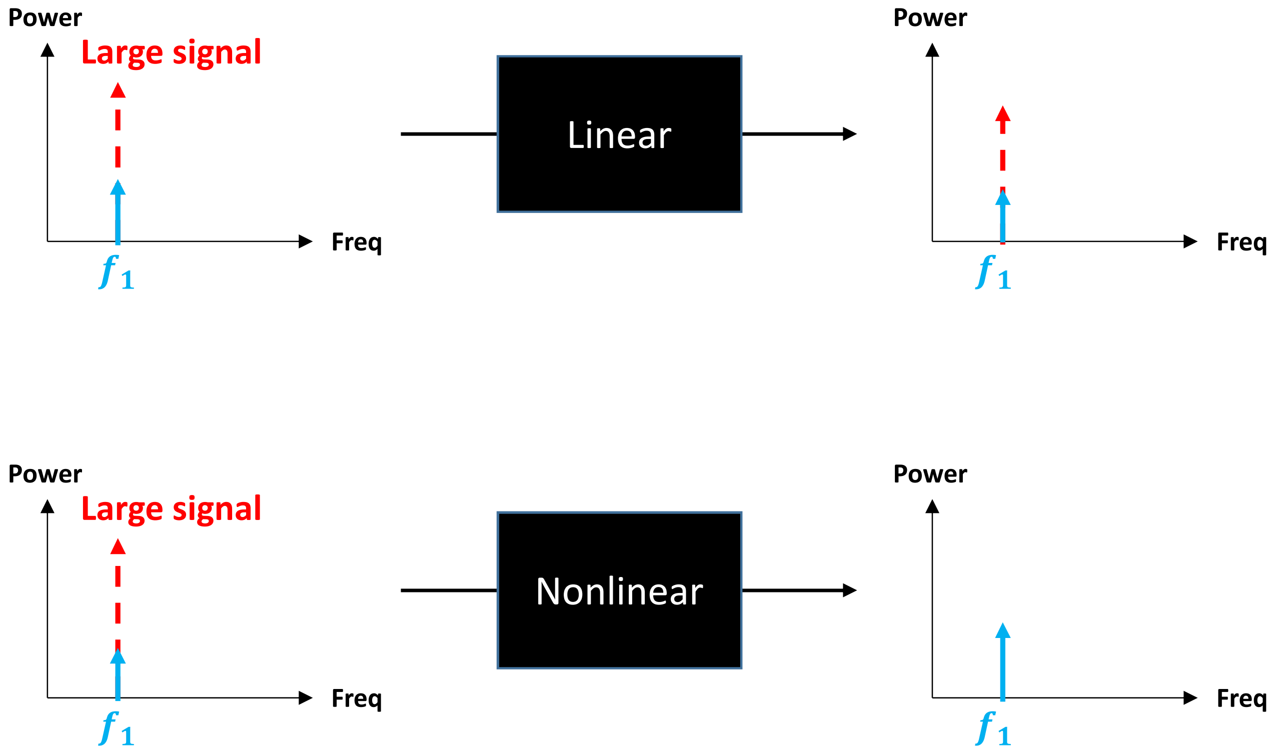

The response remains linear

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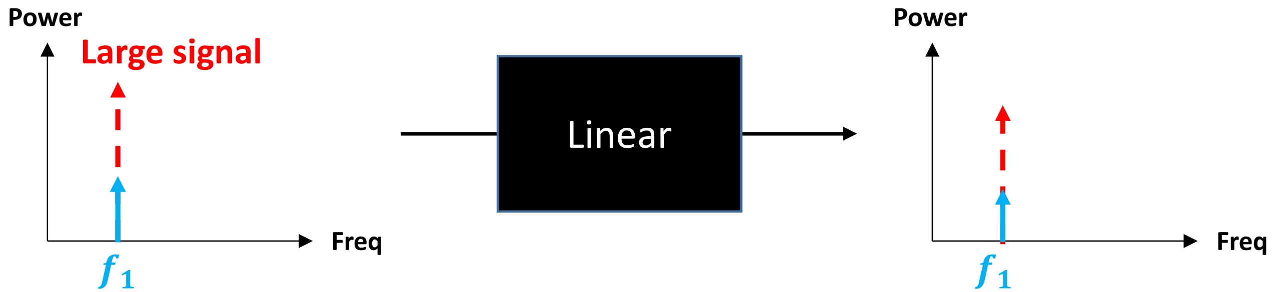
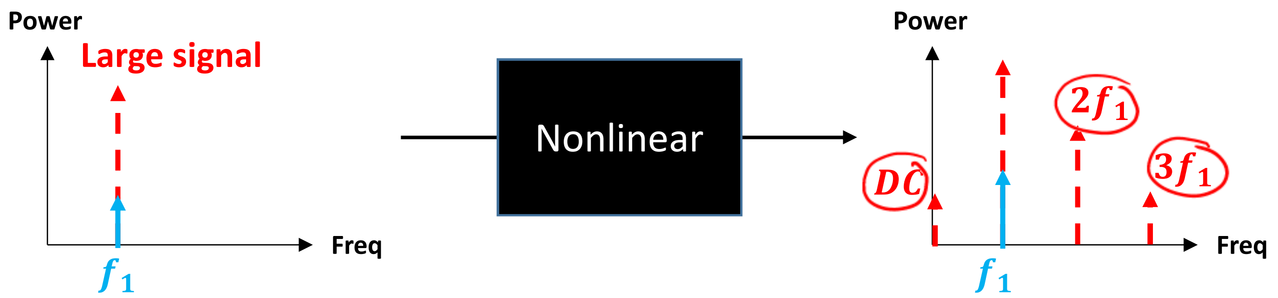
2) Linearity / Non Linearity (single carrier)



The response remains linear



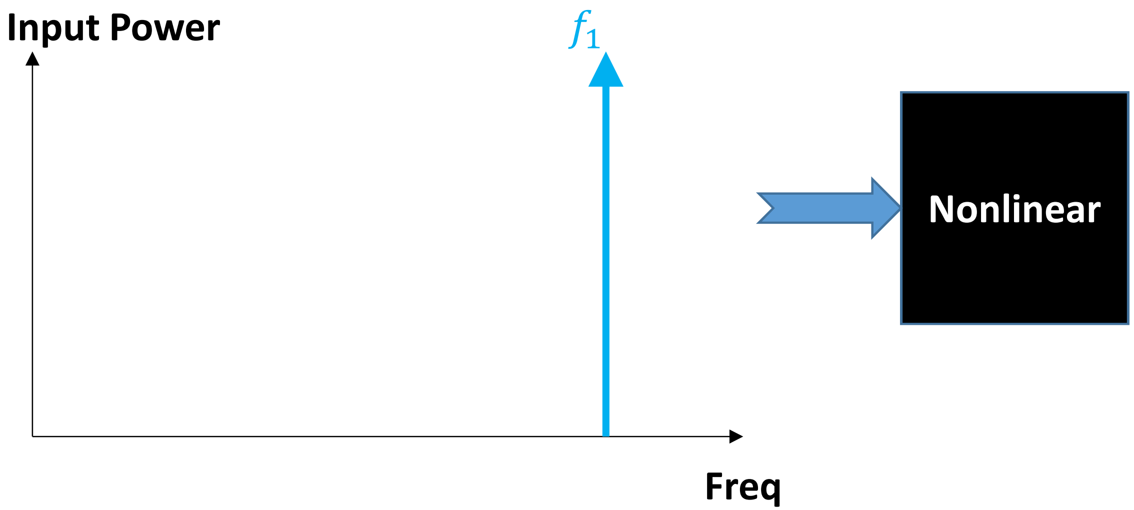
The response is nonlinear (generation of harmonics)

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

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

I - Differences Active/Passive & Linear/Nonlinear

3) Frequency generation of nonlinear devices

a) Single carrier

Illustration using a 3rd order polynomial nonlinearity

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

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 ...)

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

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

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

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

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

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

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

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

Example of 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

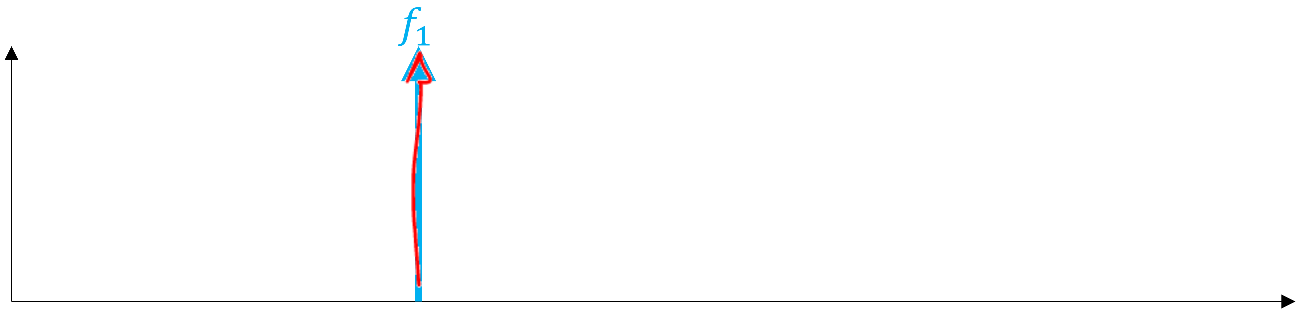
$x(t) = A\,cos(\omega_1 t)$ → **Nonlinear** → $y(t) = \boxed{a.x} + b.x^2 + c.x^3$

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

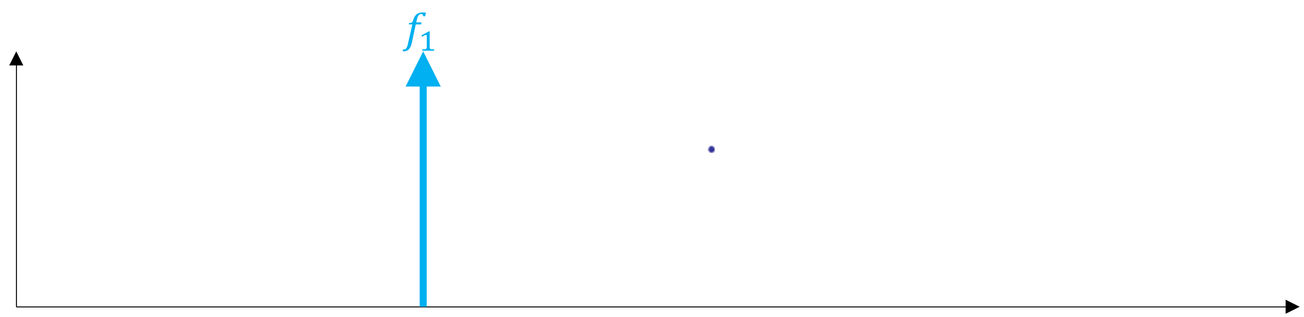
$$x(t) = A\,cos(\omega_1 t) \Rightarrow \boxed{\textbf{Nonlinear}} \Rightarrow y(t) = a.x + \boxed{b.x^2} + c.x^3$$

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

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

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

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



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

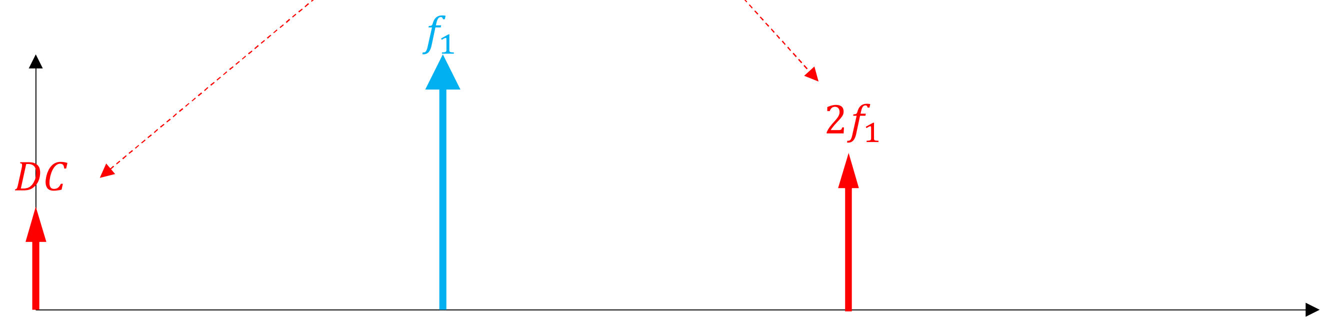
$$\frac{b.A^2}{2} + \frac{b.A^2}{2} cos(2\omega_1 t)$$

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

$$\frac{3c.A^3}{4}\overset{f_1}{cos(\omega_1 t)} + \frac{c.A^3}{4}\overset{3f_1}{cos(3\omega_1 t)}$$

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

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

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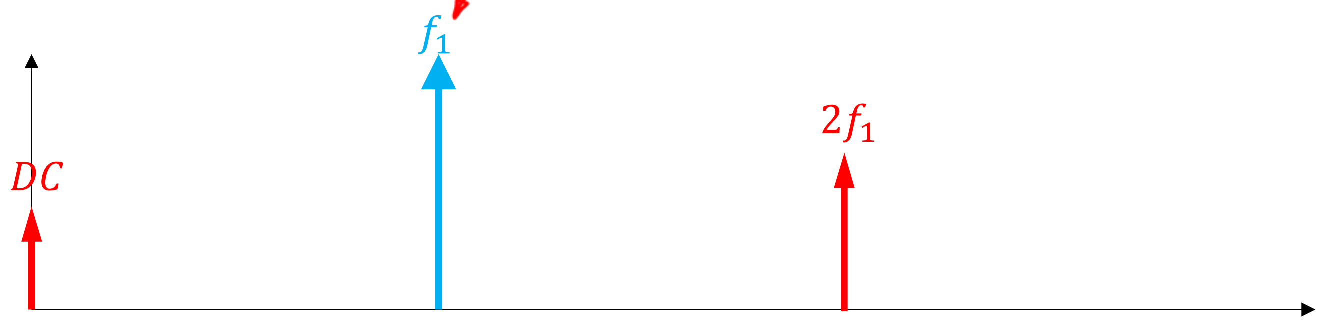

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3) Frequency generation of nonlinear devices

a) Single carrier

Illustration using a 3rd order polynomial nonlinearity

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

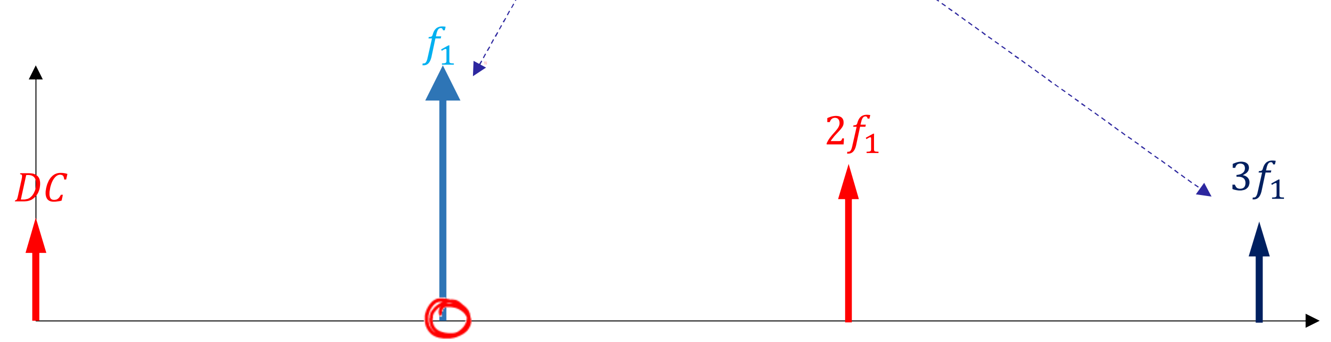
$$\frac{3c.A^3}{4}\cos(\omega_1 t) + \frac{c.A^3}{4}\cos(3\omega_1 t)$$

3rd order of nonlinearity
→ Harmonics 1 and 3

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

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

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

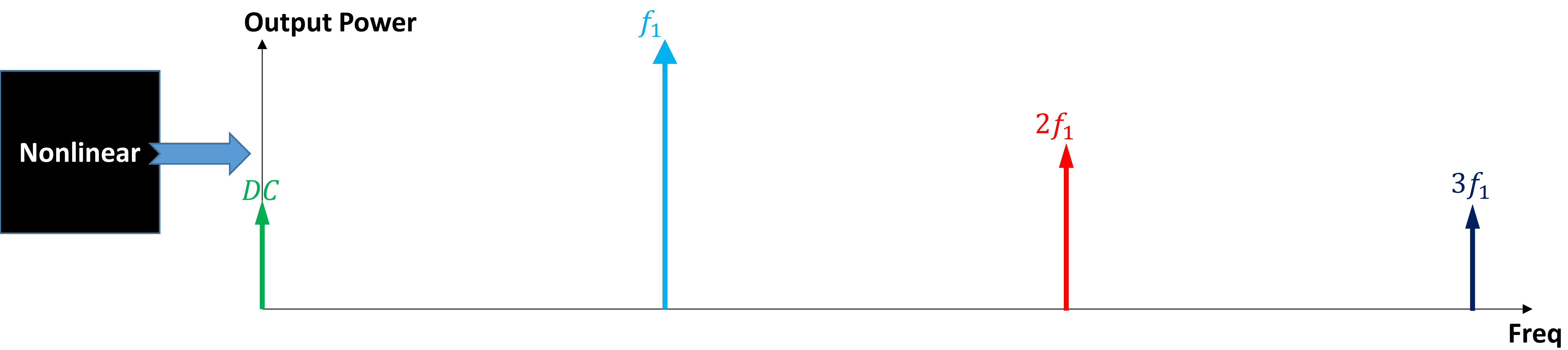


I - Differences Active/Passive & Linear/Nonlinear

3) Frequency generation of nonlinear devices

a) Single carrier

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



I - Differences Active/Passive & Linear/Nonlinear

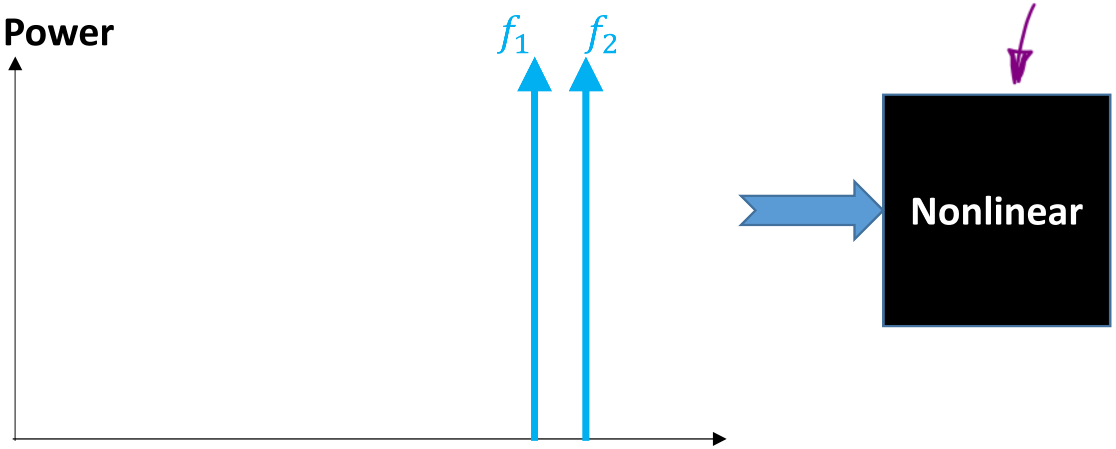
3) Frequency generation of nonlinear devices

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

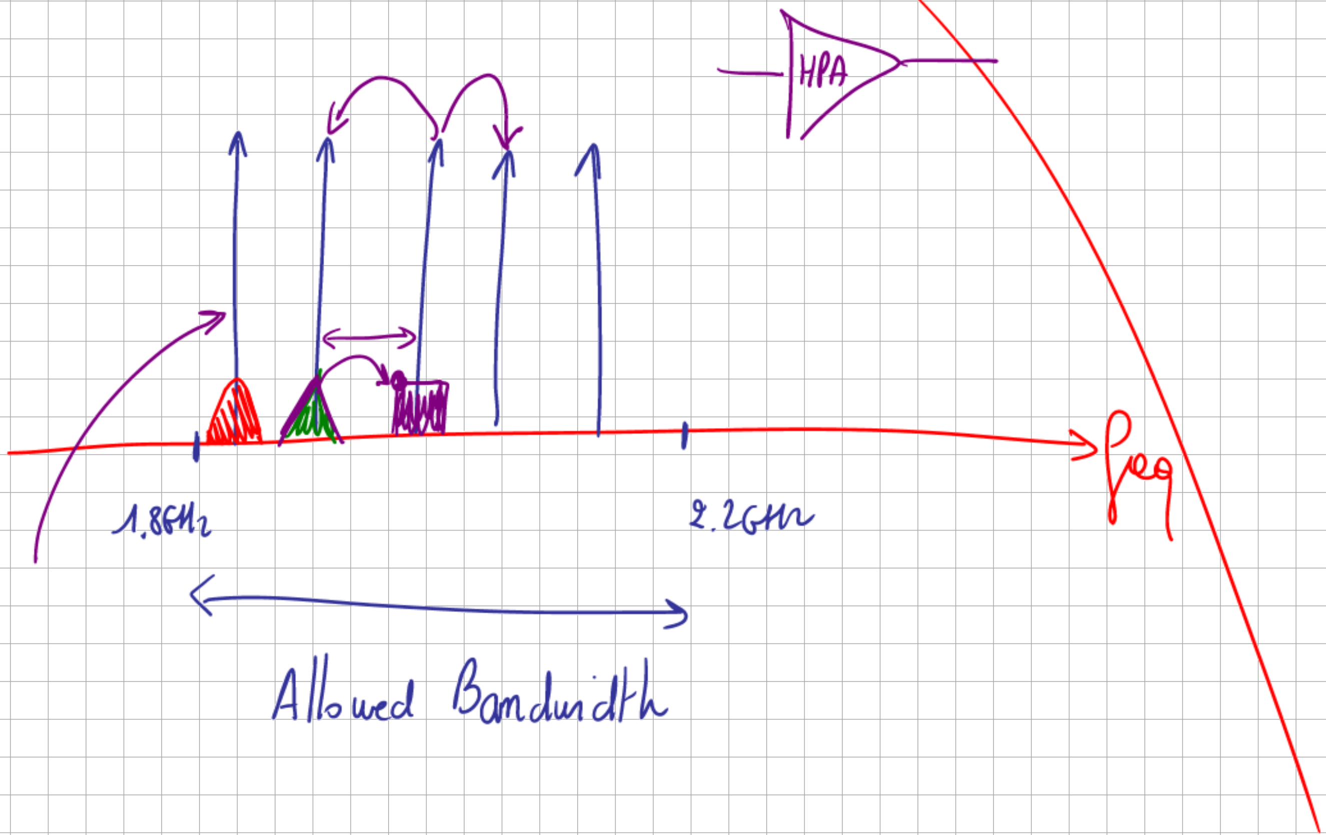
disadvantage for amplifiers required for mixers

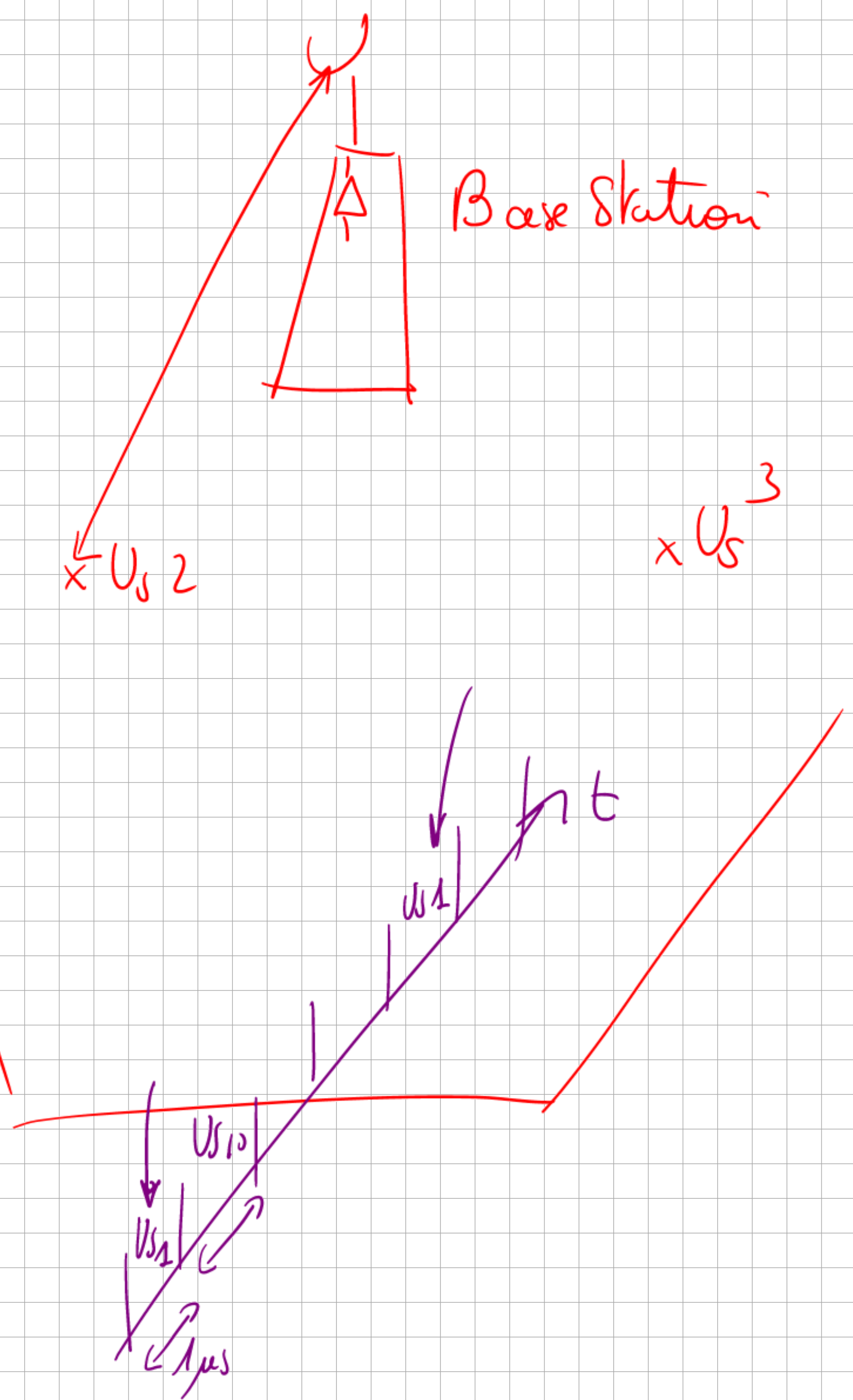
Two carriers f_1 and f_2 in a 3rd order nonlinearity

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



Multiple Access





FDMA (Frequency Division MA)

TDMA (Time ____________)

I - Differences Active/Passive & Linear/Nonlinear

3) Frequency generation of nonlinear devices

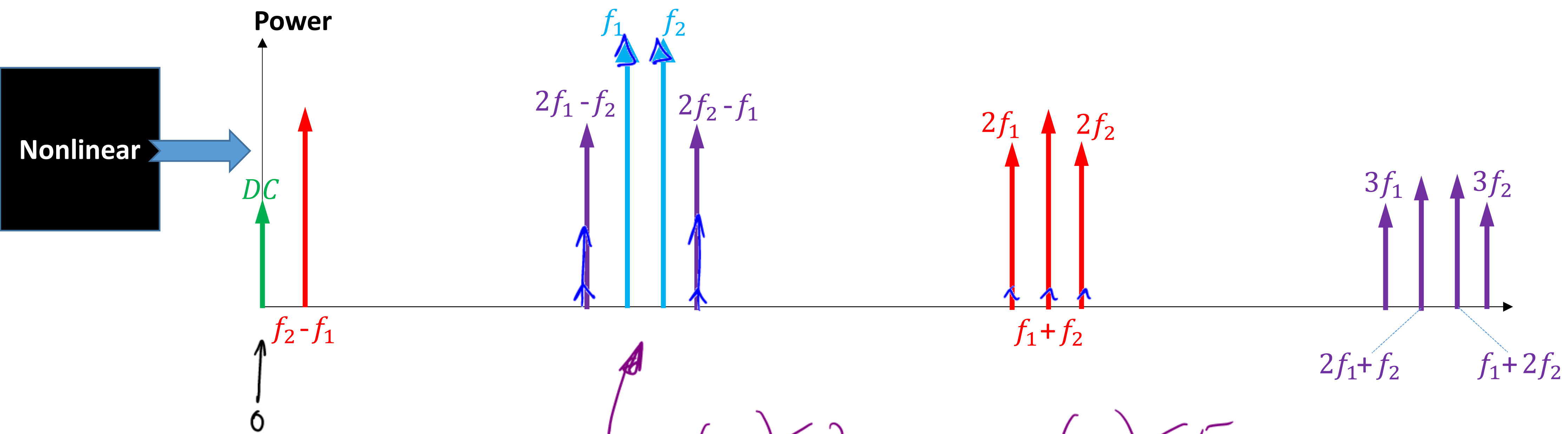
b) Multiple carriers (**example of two carriers → intermodulation products**)

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

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

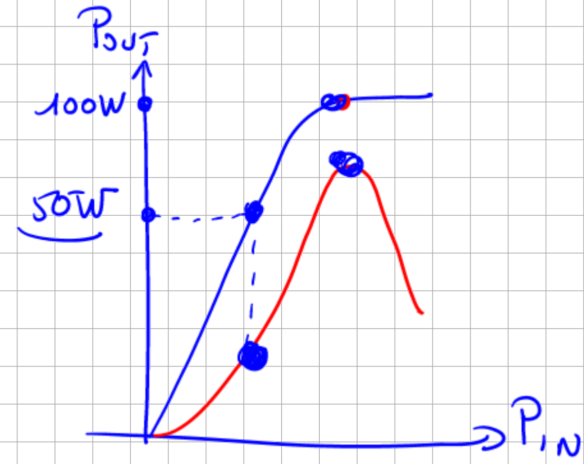
$(p+q)$ is the order of nonlinearity

or



$\max(p+q) \leq 3$ $\max(p+q) \leq 5$

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



<u>if p = 0</u> $\quad q = 0, 1, 2, 3 \longrightarrow f_2 \quad 2f_2 \quad 3f_2 \quad DC$

<u>if p = 1</u> $\quad q = 0, 1, 2 \longrightarrow f_1, \quad f_1 + f_2, \quad f_1 + 2f_2$

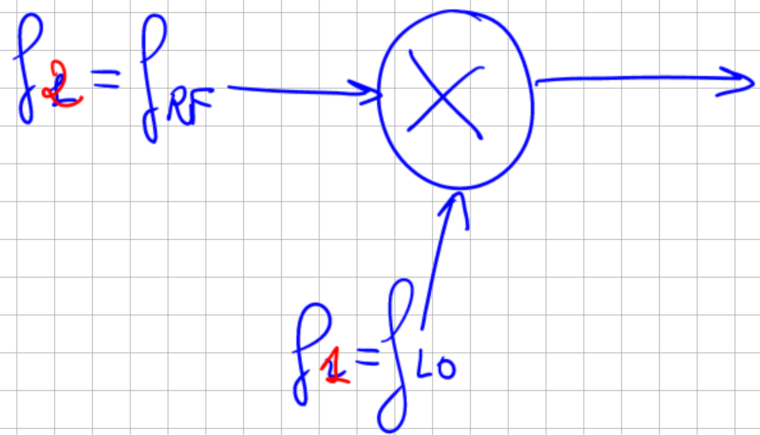
$f_2 - f_1 \quad 2f_2 - f_1$

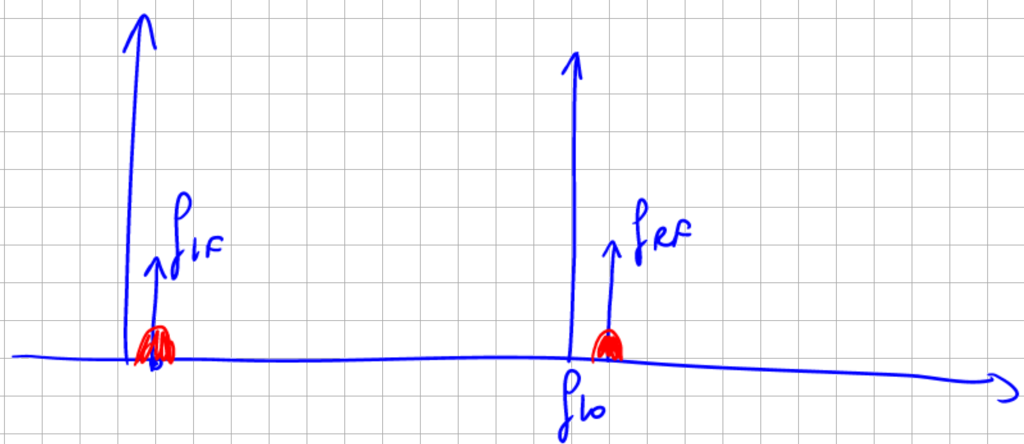
<u>if p = 2</u> $\quad q = 0, 1 \longrightarrow 2f_1, \quad 2f_1 + f_2$

$2f_1 - f_2$

$f_2 - f_1$

<u>if p = 3</u> $\quad q = 0 \longrightarrow 3f_1$





I - Differences Active/Passive & Linear/Nonlinear

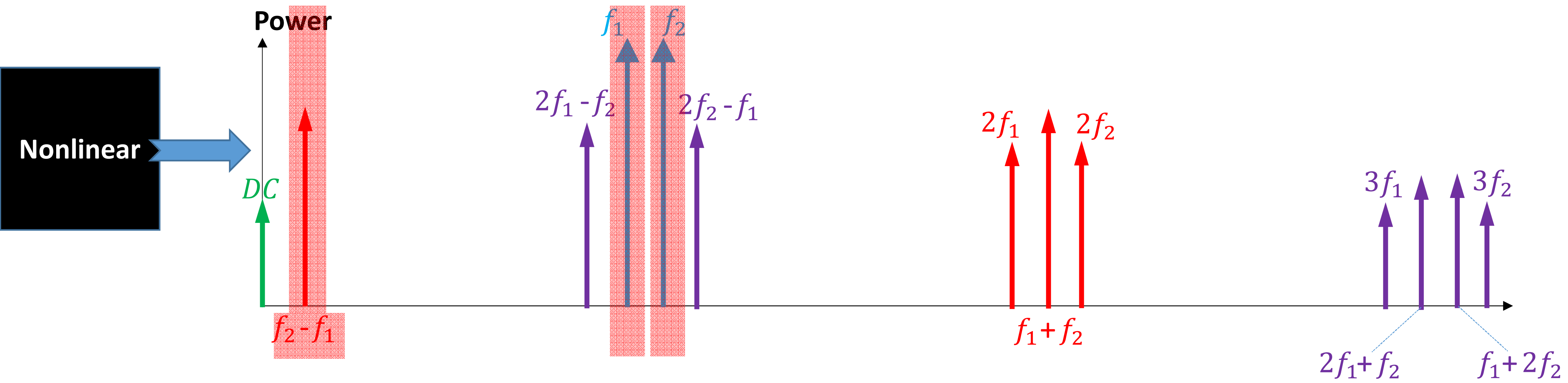
3) Frequency generation of nonlinear devices

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

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

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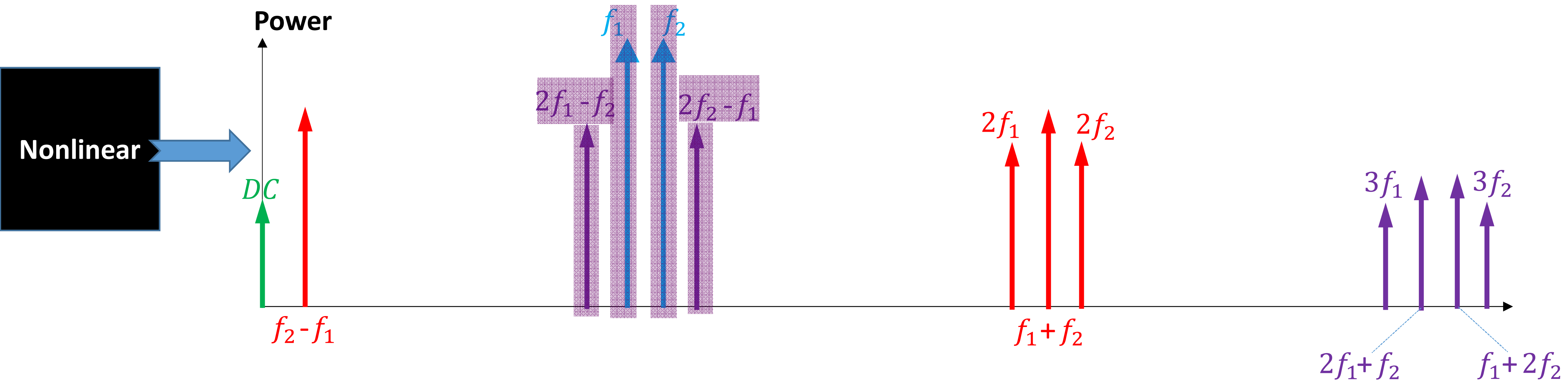
Two carriers f_1 and f_2 in a 3rd order nonlinearity → **intermodulation products** $(\pm \boldsymbol{p} \boldsymbol{f}_1 \pm \boldsymbol{q} \boldsymbol{f}_2)$ *with* $\max(p+q) \leq 3$

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

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



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

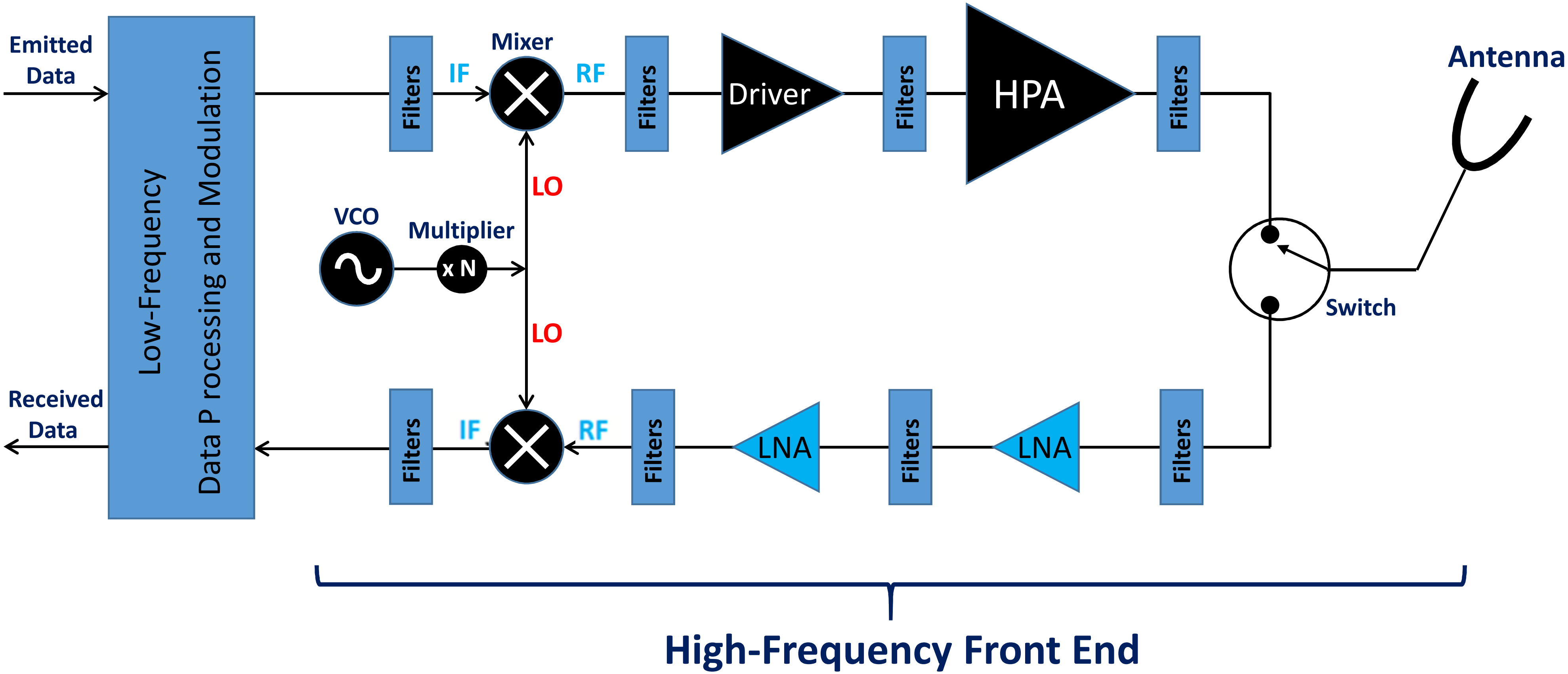
1) Low Frequency (up to 100MHz)
  - Well established consumer electronics / High level of integration / Low cost / High volumes
  - Silicon Bipolar Transistors / MOSFETs (Metal Oxyde Semiconductor FETs / BiCMOS …)

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)

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

III – High-Frequency Active Circuits in Communication Systems

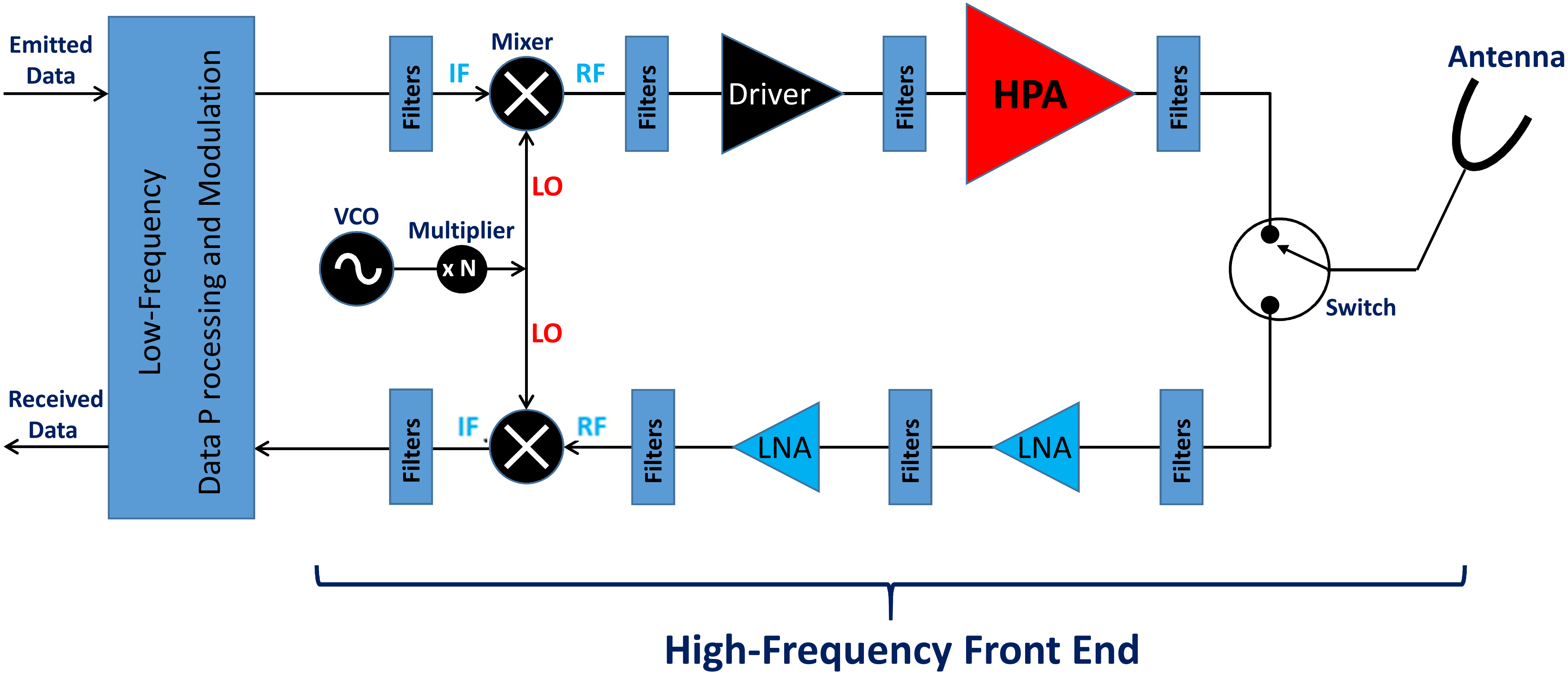
1) Example (Simplified Block Diagram of E/R Functions)



III – High-Frequency Active Circuits in Communication Systems

2) Main High-Frequency Active Circuits

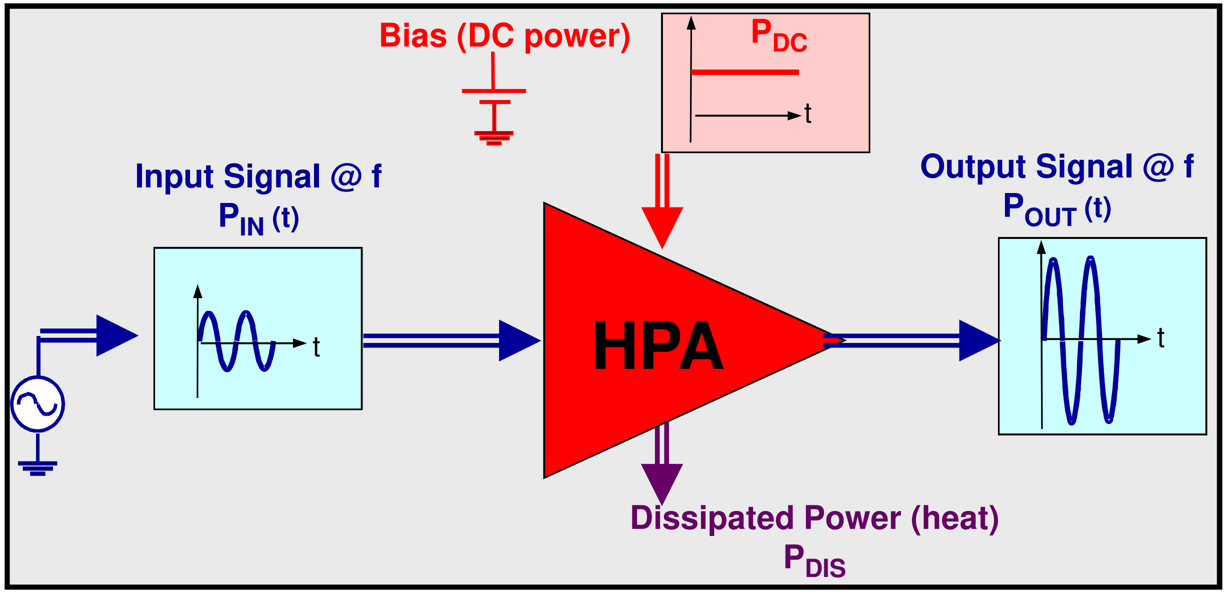
a) Amplifiers (HPA : High Power Amplifier)



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**

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

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

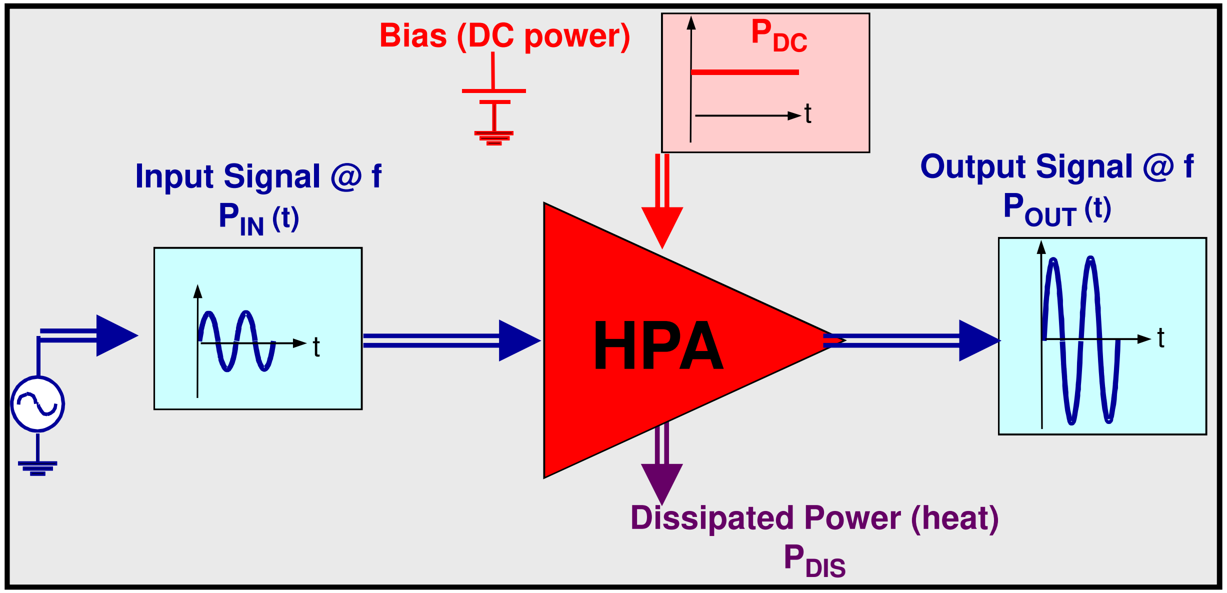
Dissipated Power **Temperature**

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

III – High-Frequency Active Circuits in Communication Systems

2) Main High-Frequency Active Circuits

a) Amplifiers (HPA : High Power Amplifier)



Only one accurate definition of efficiency

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

Power Efficiency

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

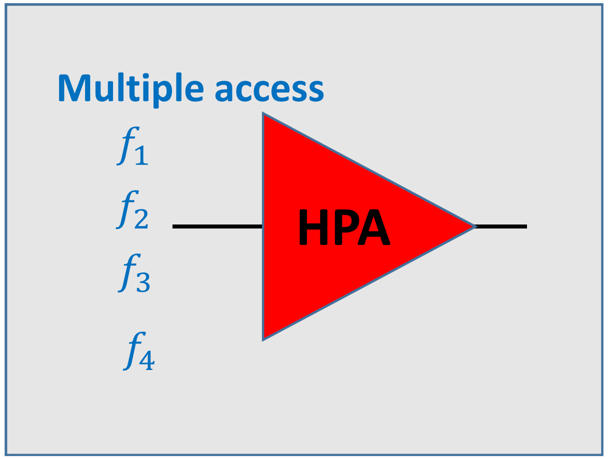
Power Added Efficiency

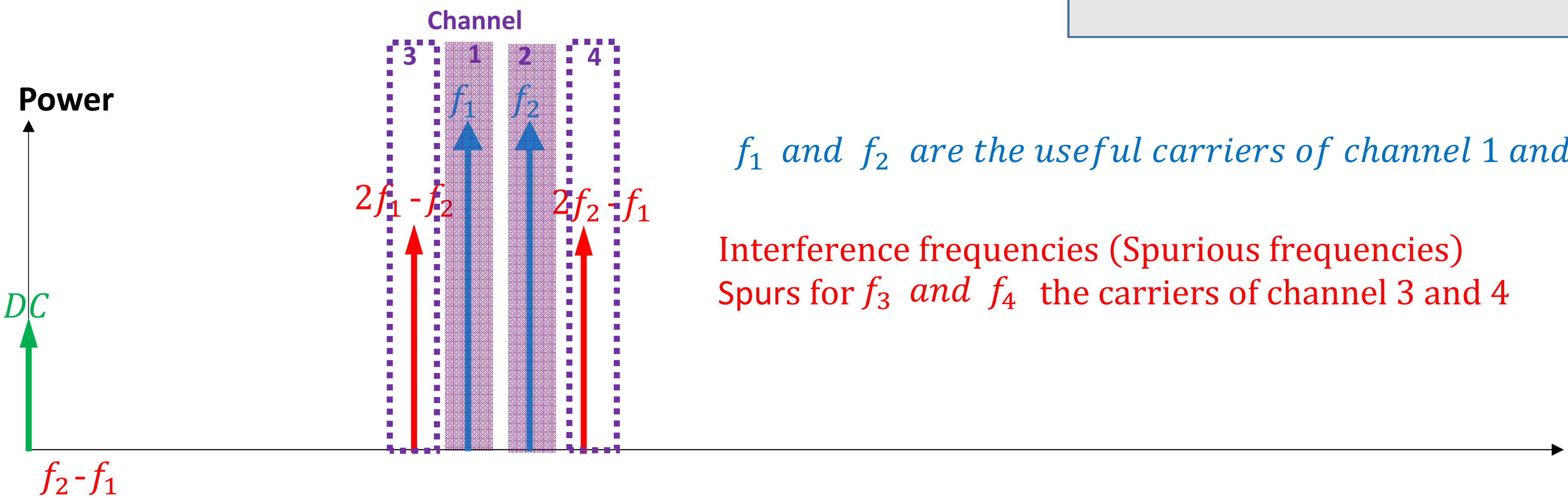
$$\mathbf{PAE} = (P_{OUT} - P_{IN}) / P_{DC}$$

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





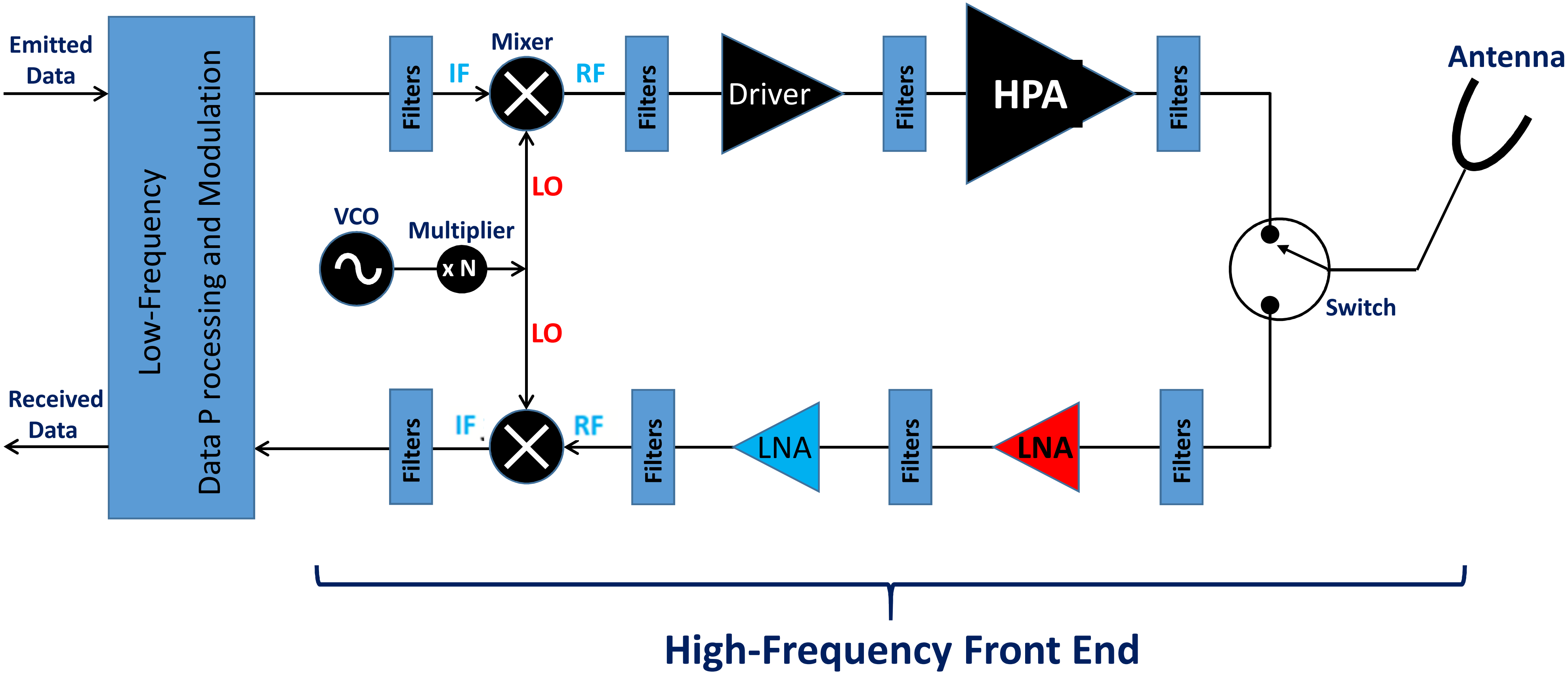
f_1 *and* f_2 *are the useful carriers of channel* 1 *and* 2

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

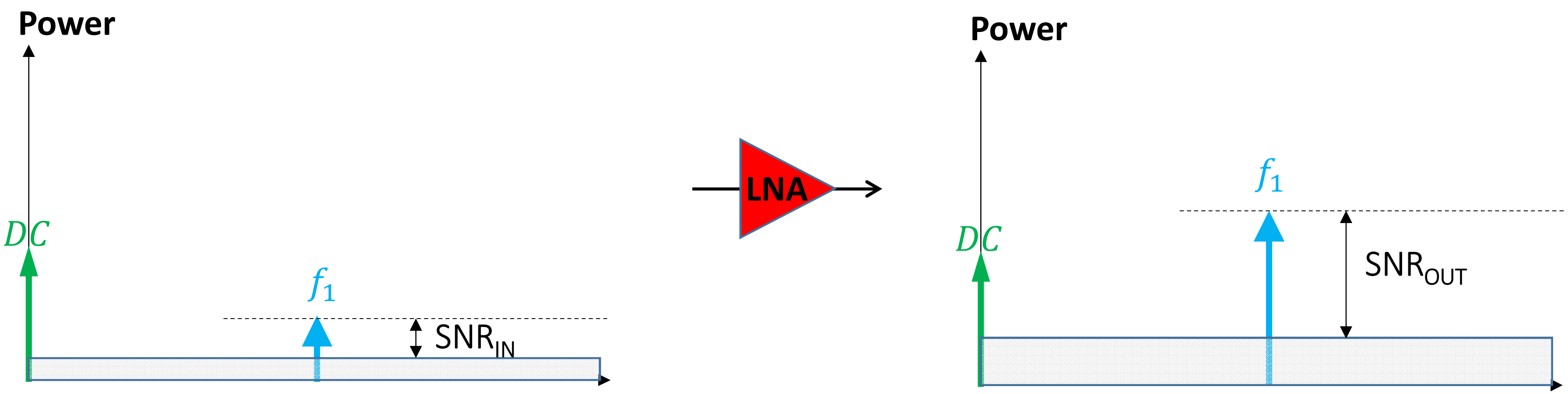
2) Main High-Frequency Active Circuits

b) **Amplifiers (LNA : Low Noise Amplifier)**



LNA (Low Noise Amplifiers)

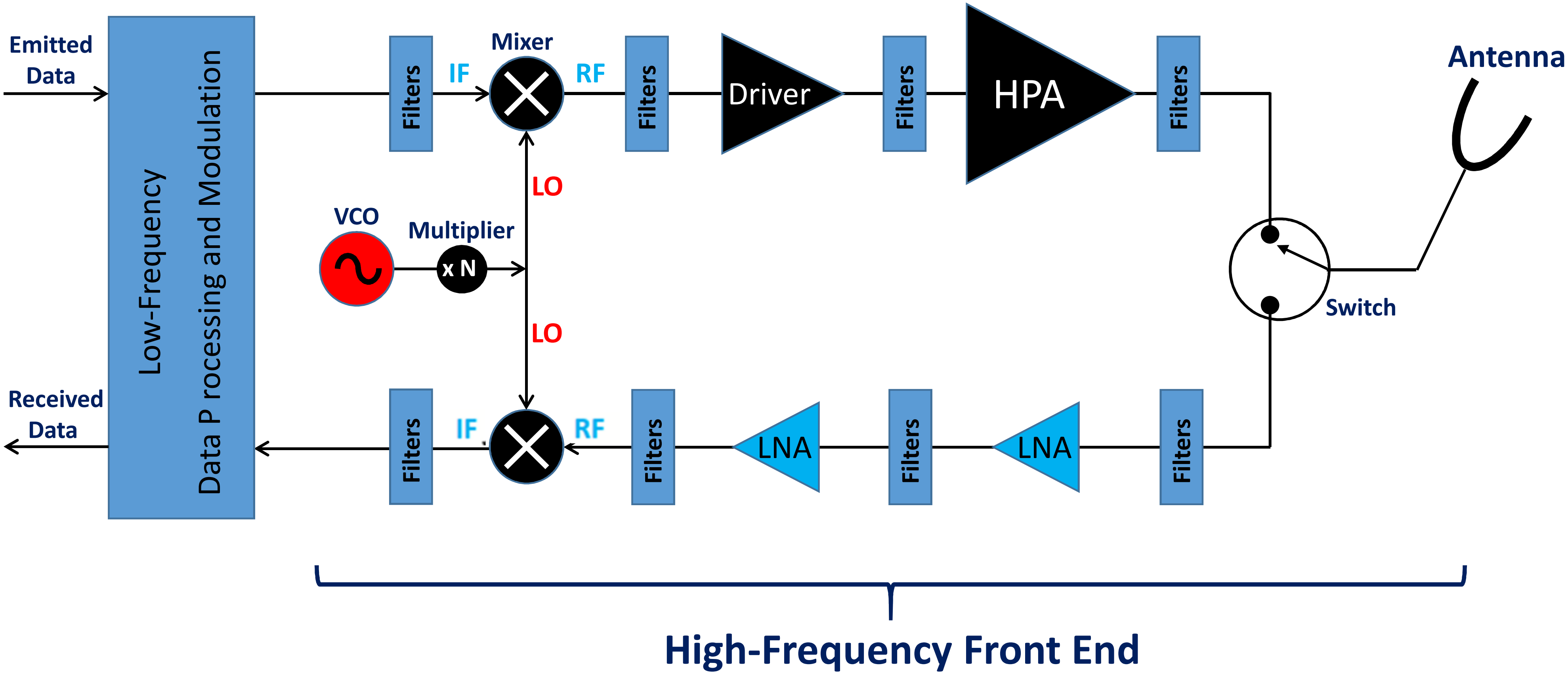
- Optimisation of Signal to Noise Ratio for LNAs → Noise property of LNA (Noise Factor)
- Increase the Signal to Noise Ratio (SNR)
- Linear operation due to the reception of very weak signals which have to be greater than the noise floor



III – High-Frequency Active Circuits in Communication Systems

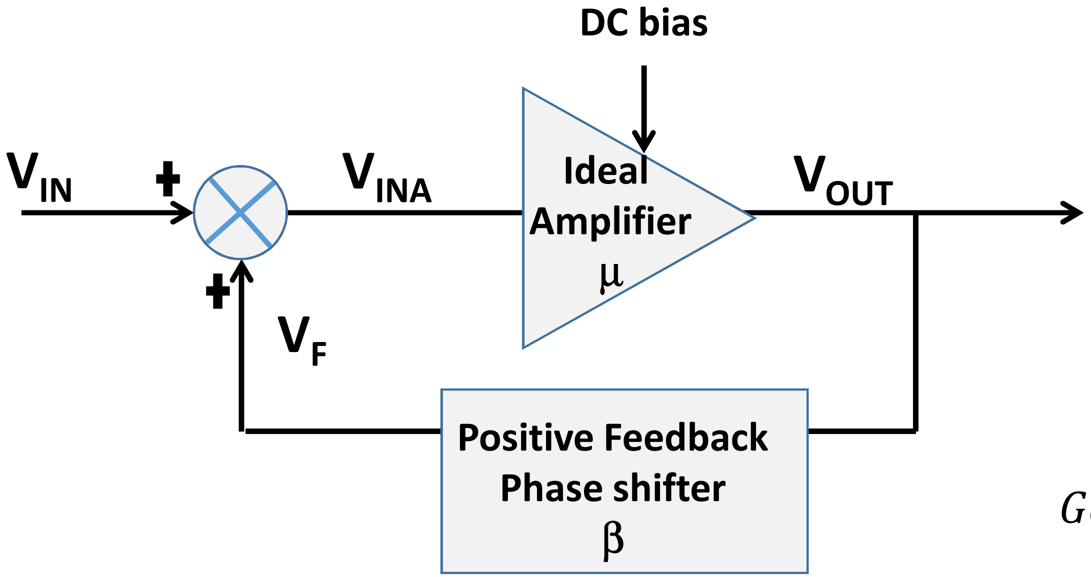
2) Main High-Frequency Active Circuits

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)



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

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

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

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 $\arg(\beta\mu)_{@\omega_{osc}} = 2\pi n$

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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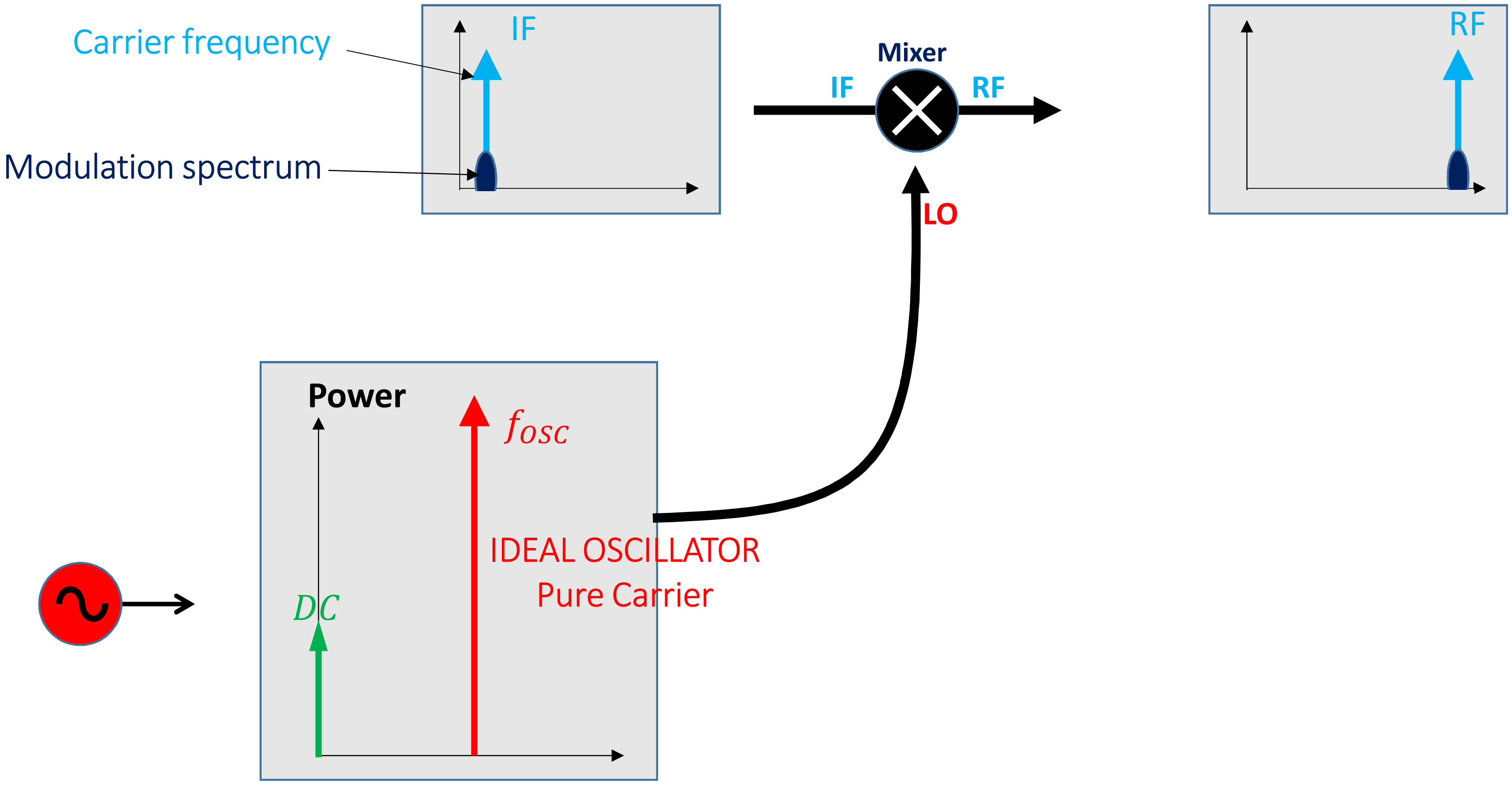

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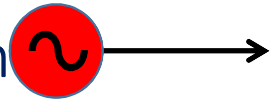

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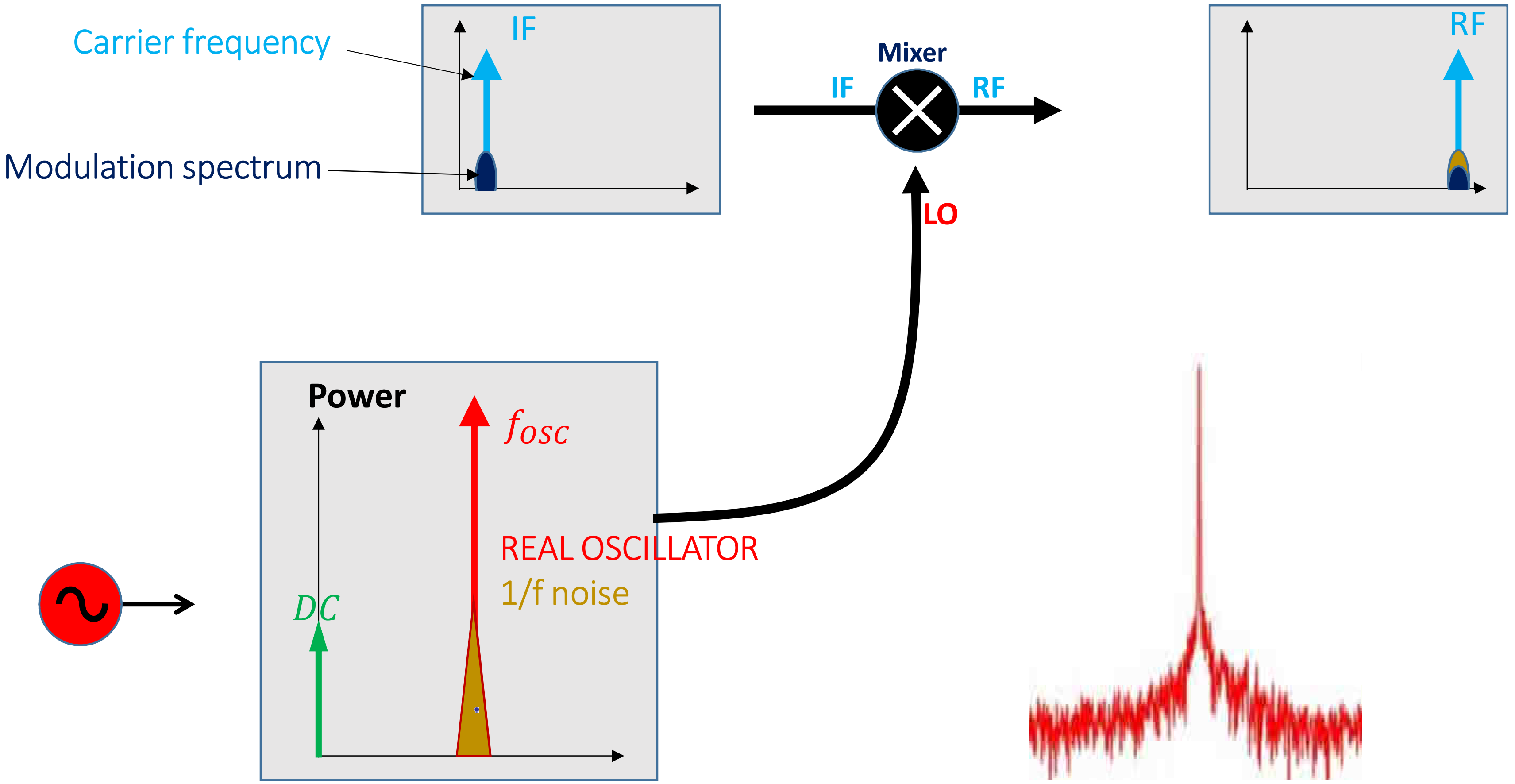
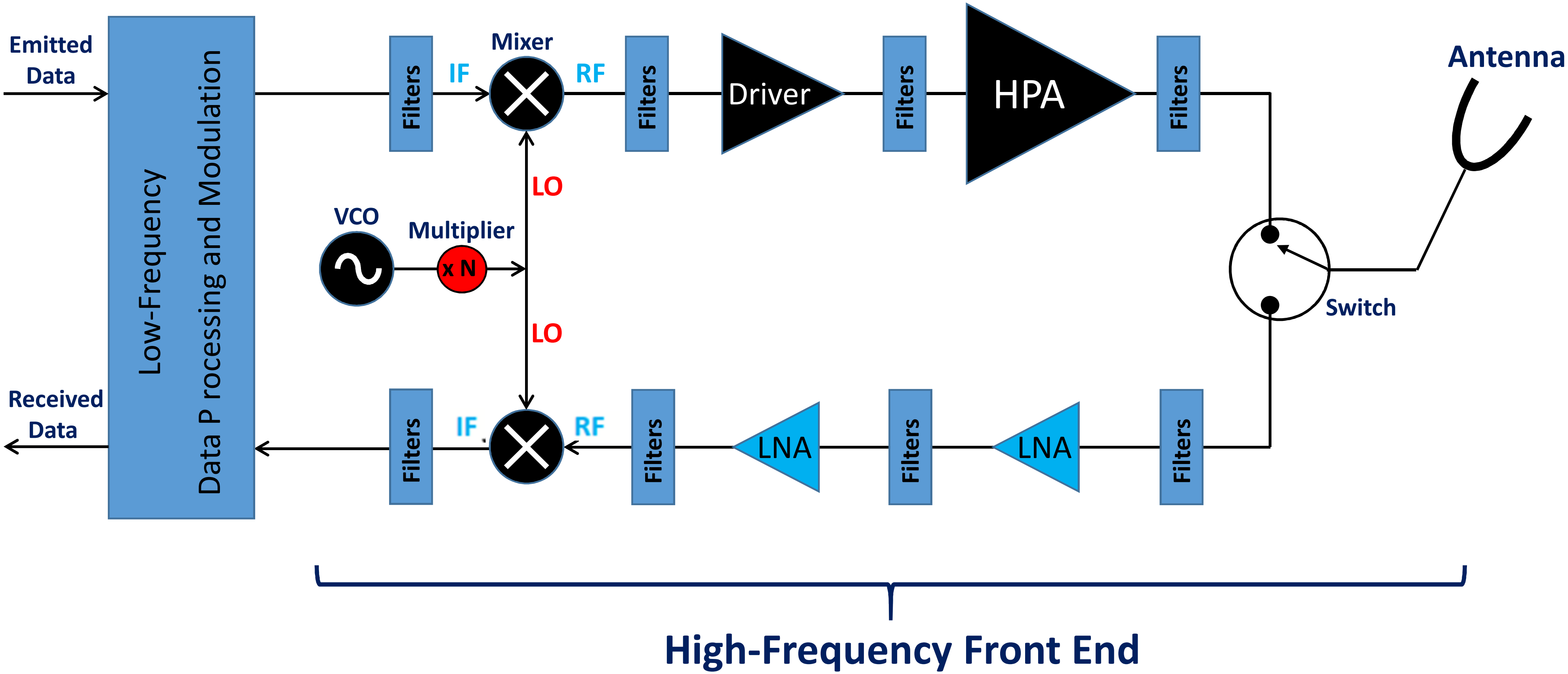


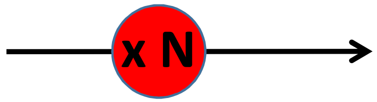
III – High-Frequency Active Circuits in Communication Systems

2) Main High-Frequency Active Circuits

d) **Multipliers**

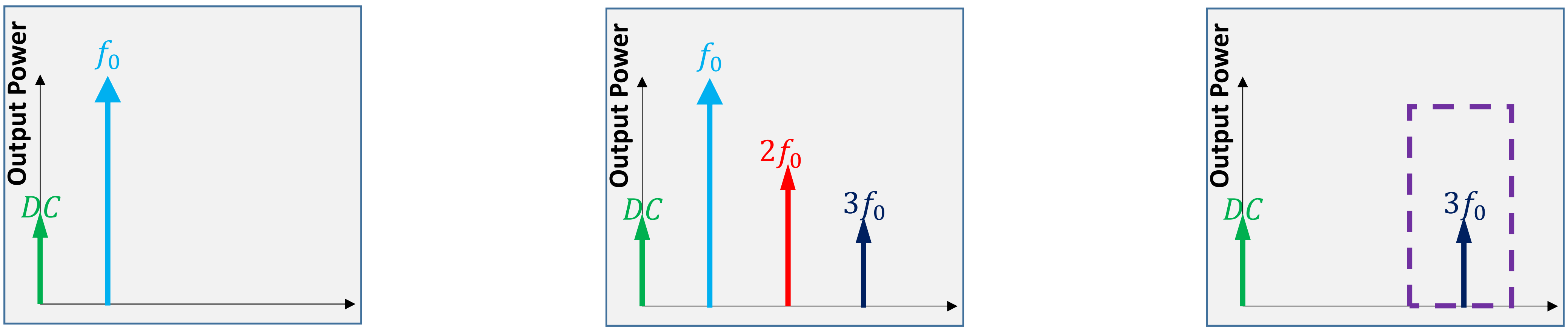


Block diagram of a frequency multiplier



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

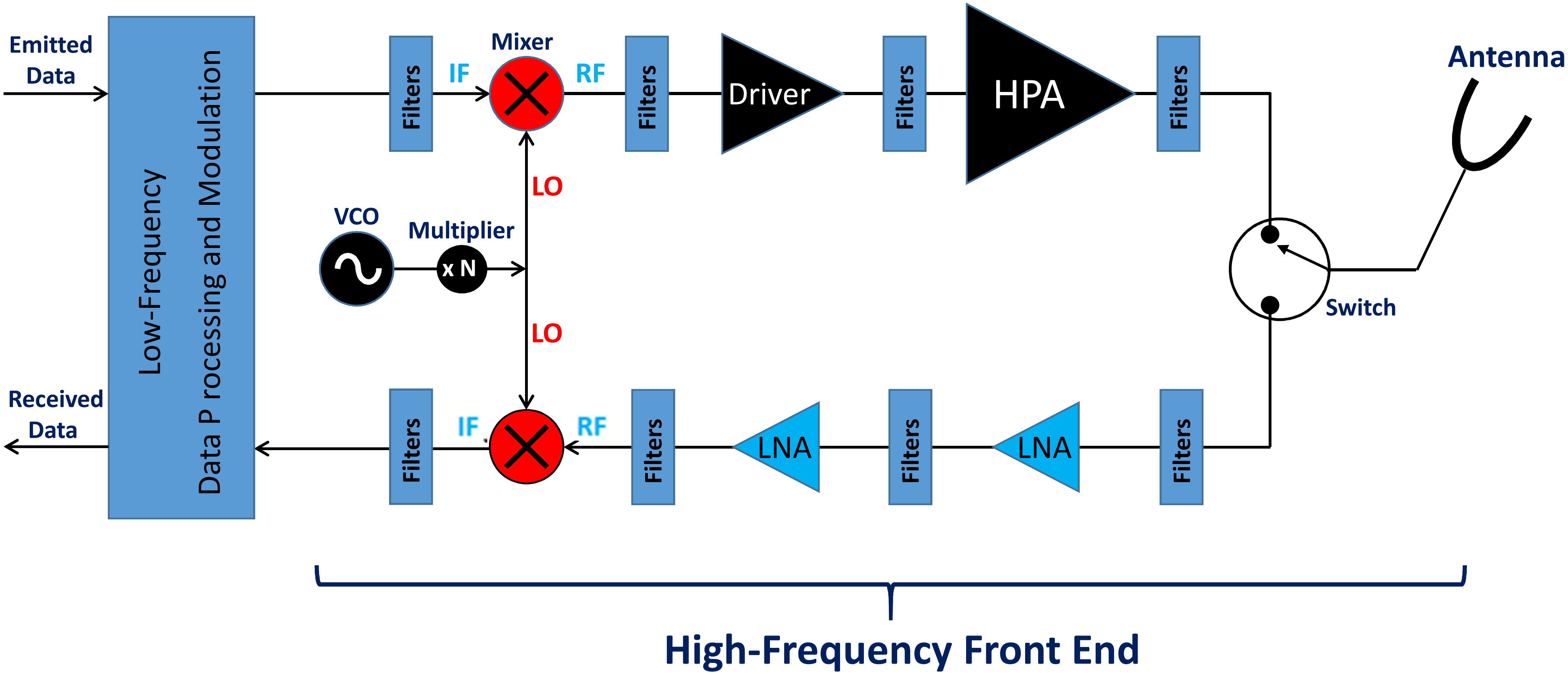
Example of tripler



III – High-Frequency Active Circuits in Communication Systems

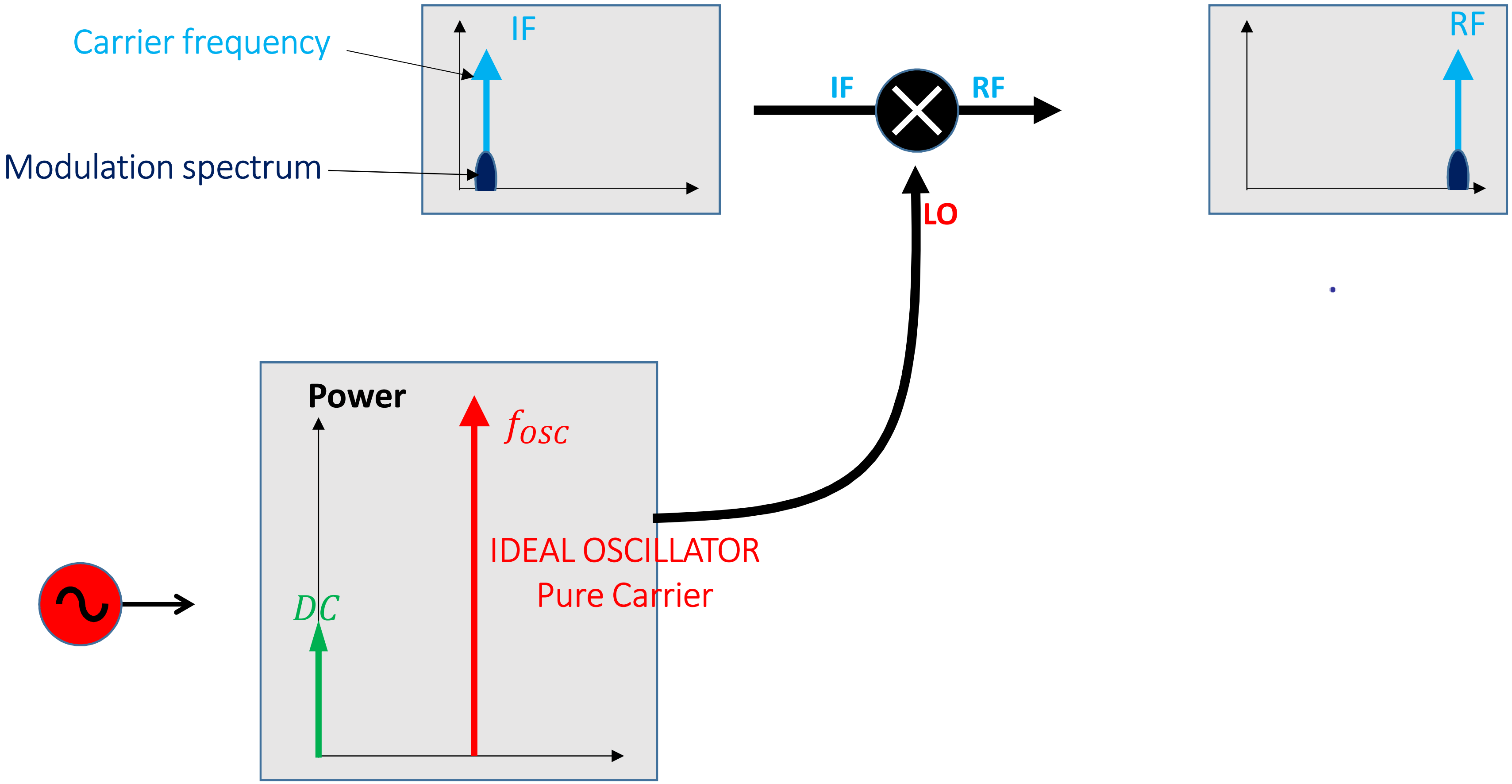
2) Main High-Frequency Active Circuits

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



Issues of mixer designs (Conversion gain, Isolations…)

Ideal Mixer



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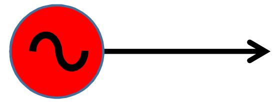
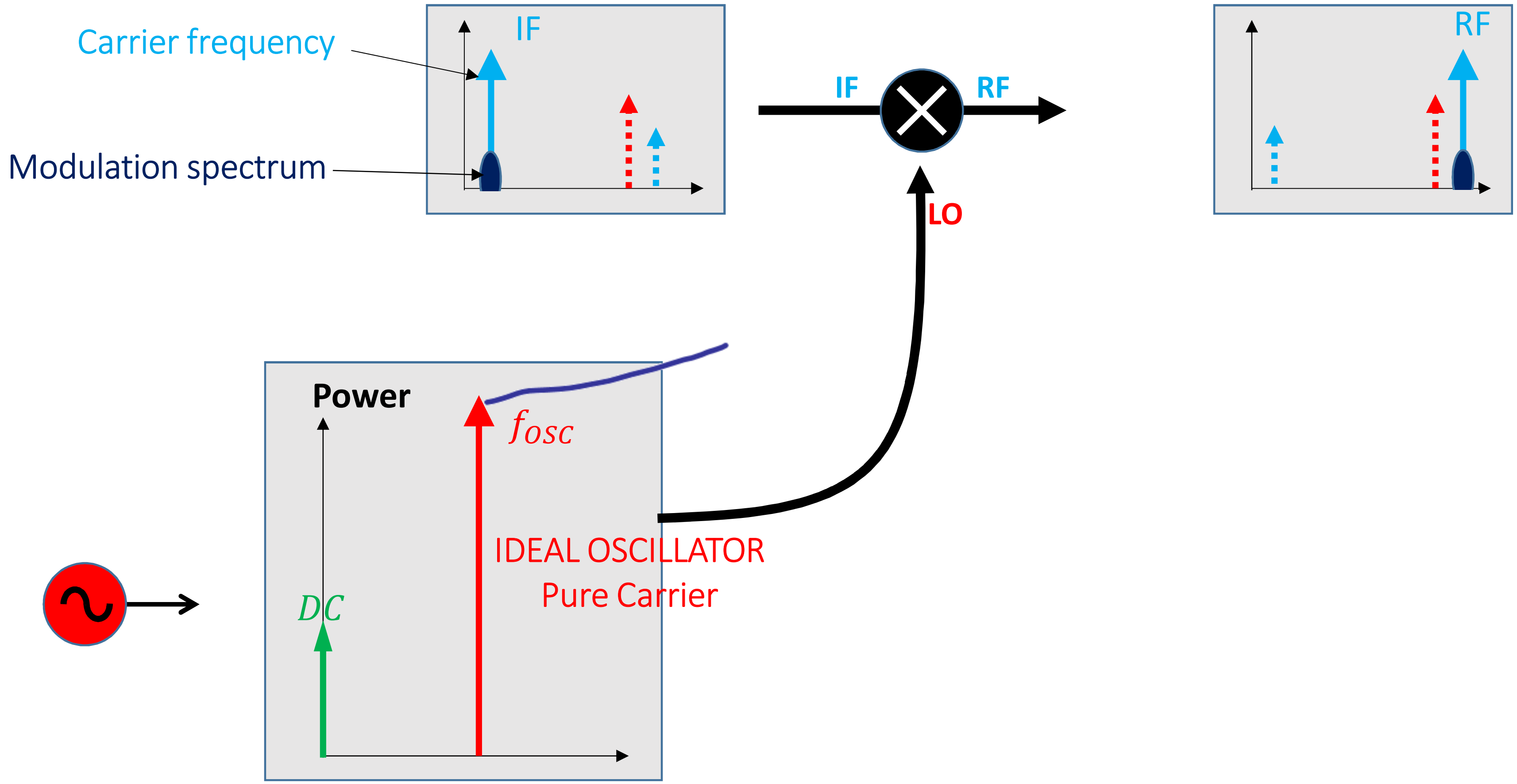


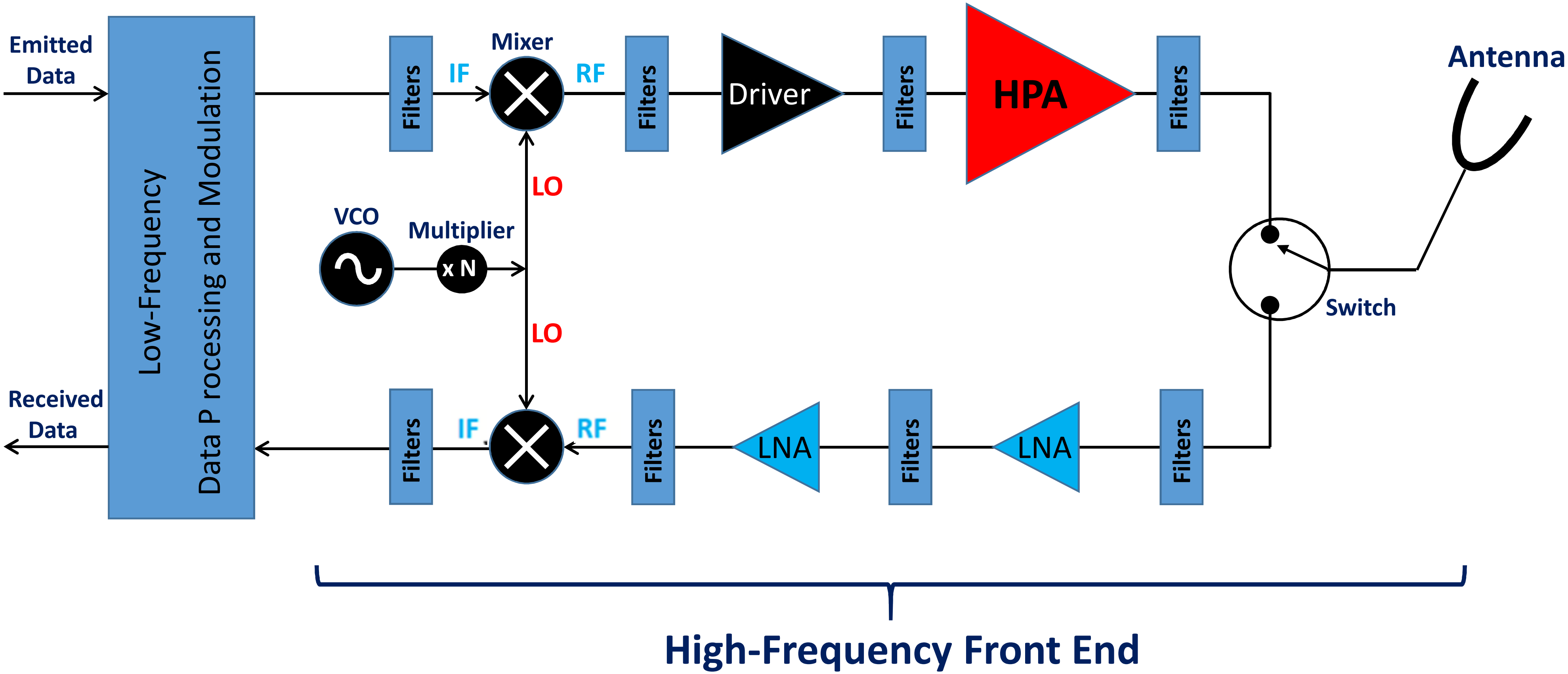
Real Mixer



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**

- ET (Envelope Tracking)

- DOHERTY

- LINC (Linear amplification with Nonlinear Components)

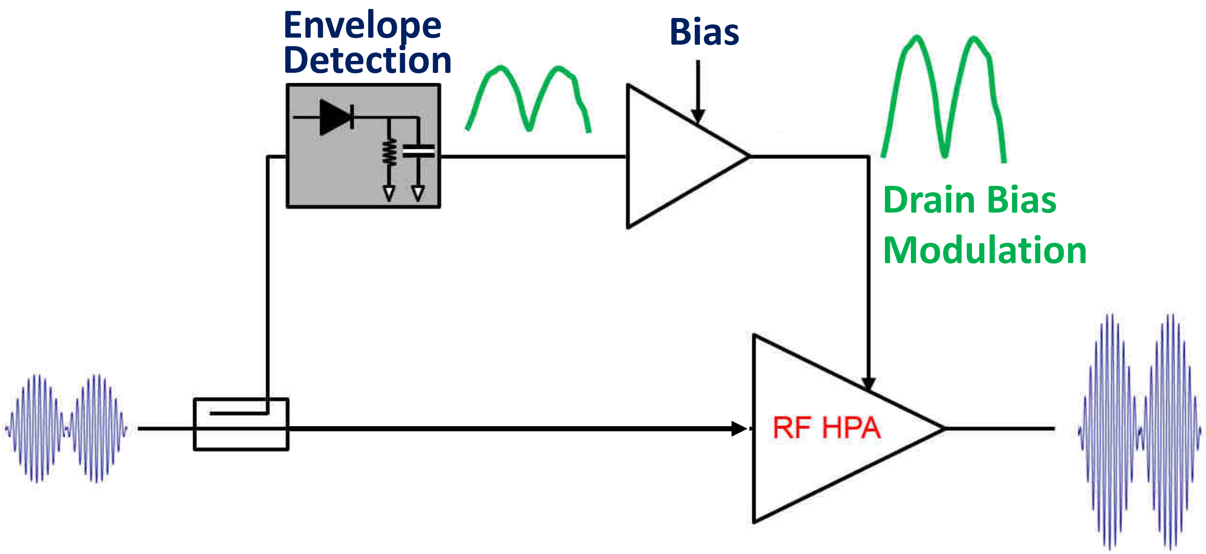
III – High-Frequency Active Circuits in Communication Systems

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**



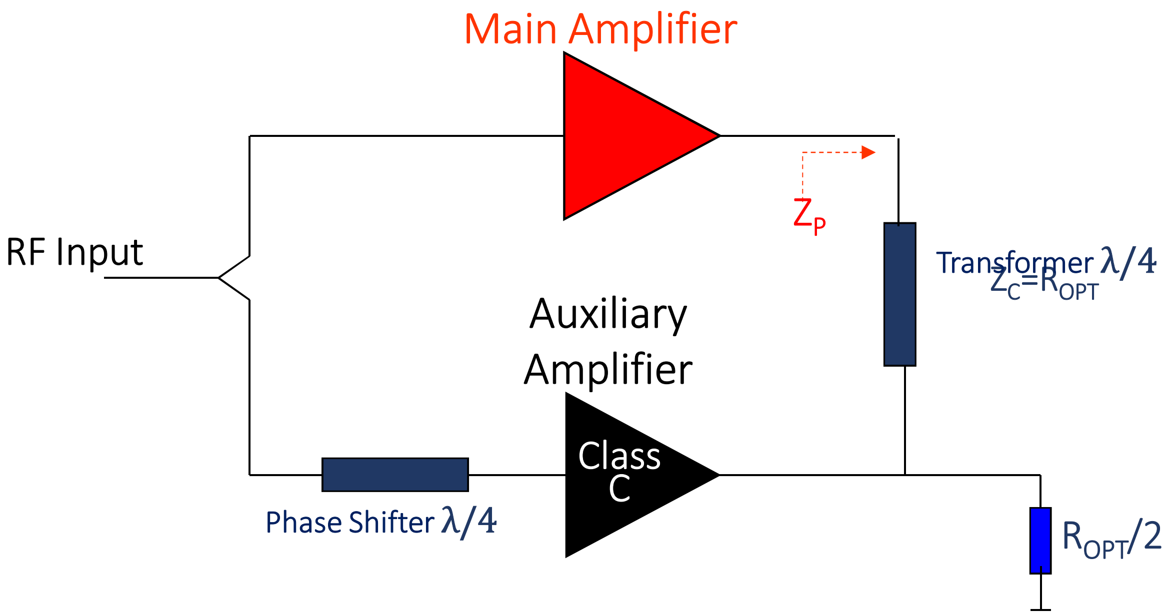
III – High-Frequency Active Circuits in Communication Systems

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**



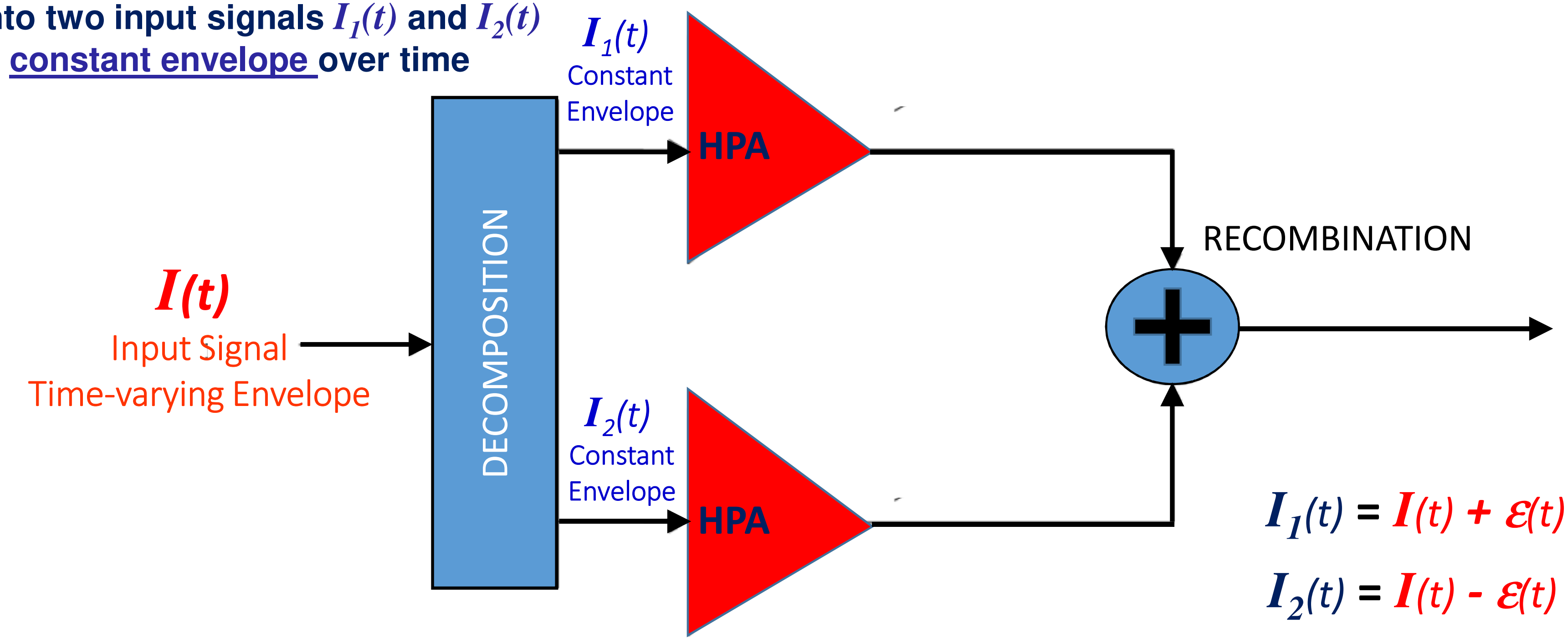
III – High-Frequency Active Circuits in Communication Systems

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} (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)