ICS 905: Fundamentals in AMS&RF Electronics (FARE)

Introduction on Wireless Communication Systems – ICS 905

Futures Trends for Wireless Communication Systems

Basic concepts in RF design

Transceiver architecture

Design Examples

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ICS 905 : Fundamentals in AMS&RF Electronics (FARE)

https://ecampus.paris-saclay.fr/course/view.php?id=8876#section-2

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- **Administrative management :**
  - ICS 905 : Danielle Deloy

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Introduction on

Wireless Communication Systems

Where are systems for wireless communications ?

- Objects that we use everyday in commercial applications (smartphones & tablets, Internet boxes, Global Positioning System (GPS) & Galiléo (new generation in 2024?))

Image: Reuters

Slide : Antoine Khy

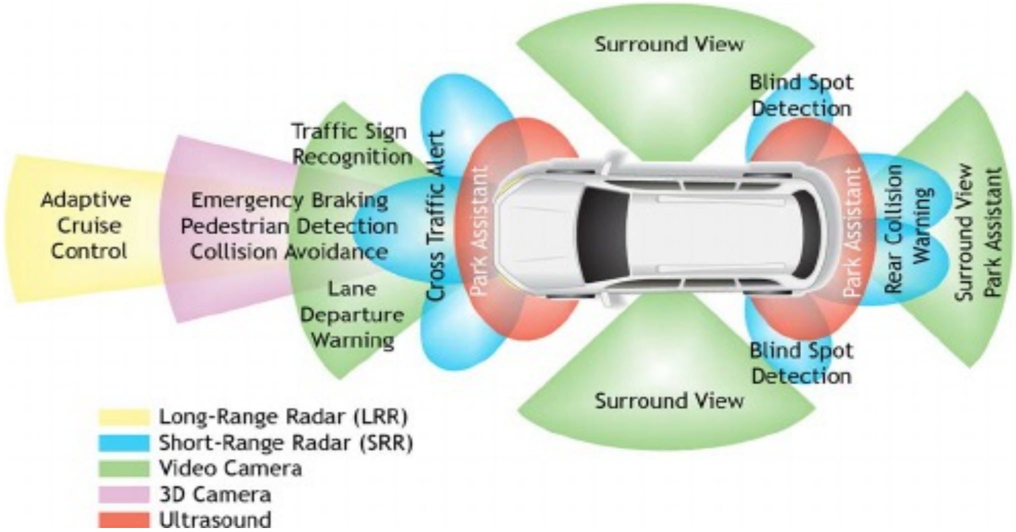
Where are systems for wireless communications ?

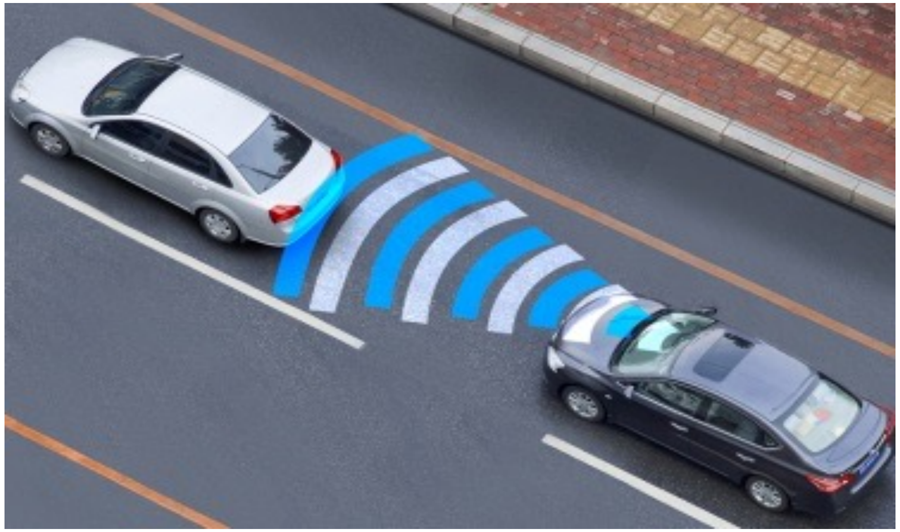
- **IoT** = Internet of Things (smart watches, glasses, shoes, fridges, TV, ovens,…)

Slide : Antoine Khy

Where are systems for wireless communications ?

- **Autonomous Cruise Control (ACC) radars (speed regulation, emergency braking, blind spot detection, collision avoidance,…)**





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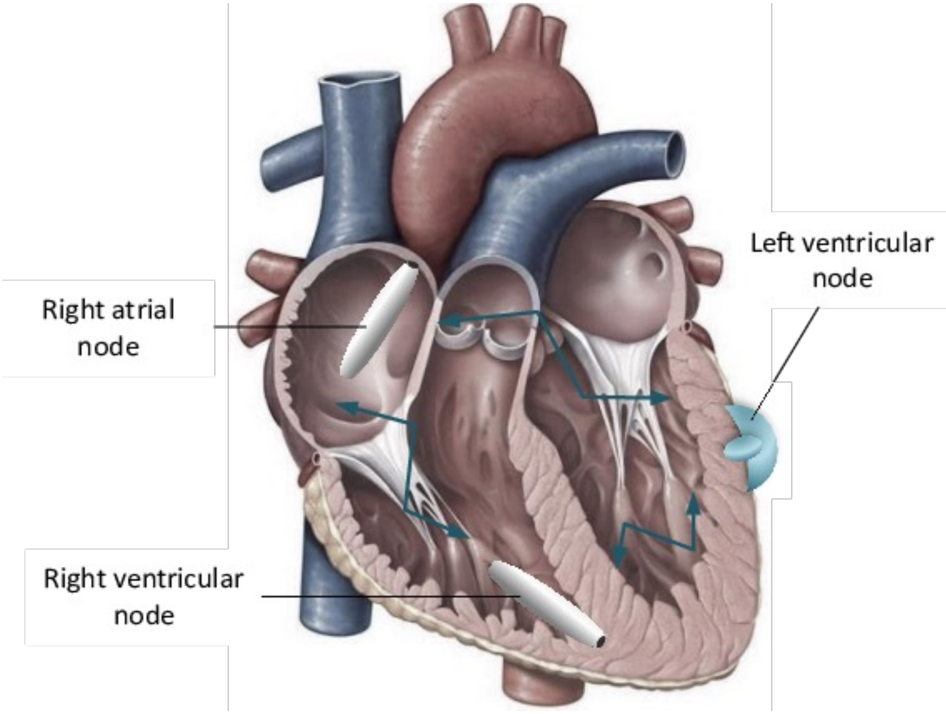
Where are systems for wireless communications ?

- **Biomedical application : Transceiver design for implant communication system with power management**

- Leadless Cardiac Pacemaker (LCP) are capsules fixed endocardially in the heart integrating all the functionalities of standard pacemakers.
- Current LCP can only pace the right ventricle (RV) → limited patient population (≈5%)
- A multi-nodal LCP system requires a communication network to synchronize the delivery of therapy stimuli.
- Intra-Body Communication (IBC) is a promising solution since it requires less power compared to standard RF communications.



Where are systems for wireless communications ?

- **Objects used in specific applications: Satellite communications (TV broadcasting, weather forecast, Earth observation,…)**

Slide : Antoine Khy

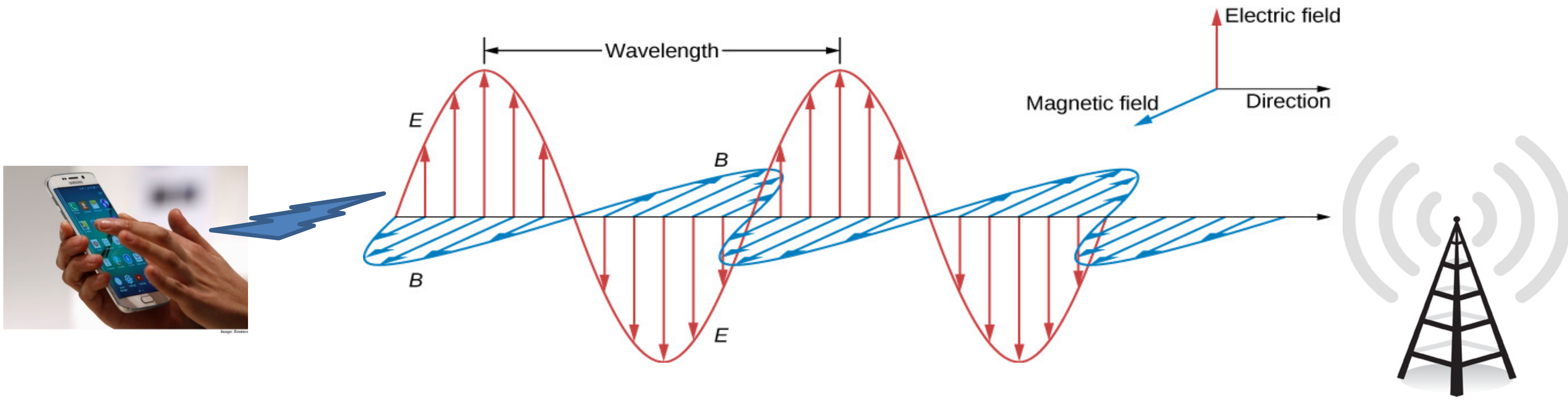
Where are systems for wireless communications ?

- **Objects used in specific applications: Military & Defense (detection, surveillance, guidance & weapons systems)**

What are the characteristics of systems for wireless communications ?

- **1 – Propagation of data in the air by Electromagnetic (EM) waves radiated by means of antennas…**

… without any cable or wire, hence the term « wireless »



What are the characteristics of systems for wireless communications ?

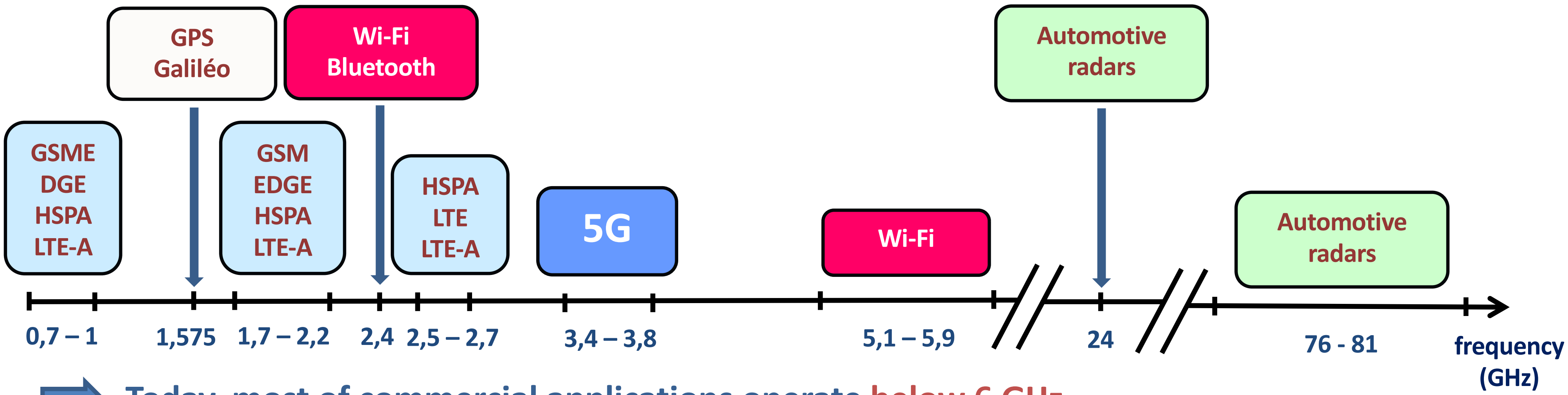
- 2 – Very high frequency of operation, typically 0,1 - 100 GHz = RF (Radio-Frequency)

  For commercial applications …

  – Wireless communications standards : GSM (2G), GPRS (2.5G), EDGE (2.75G), WCDMA (3G), HSPA (3.5G), LTE (3.9G or 4G), LTE-Advanced (4G or 4.5G), LTE-Advanced Pro (4.5 or 4.9G), 5G, Wi-Fi, Bluetooth, …

  – Geolocation systems (GPS, Galiléo)

  – Automotive radars



➡ Today, most of commercial applications operate below 6 GHz

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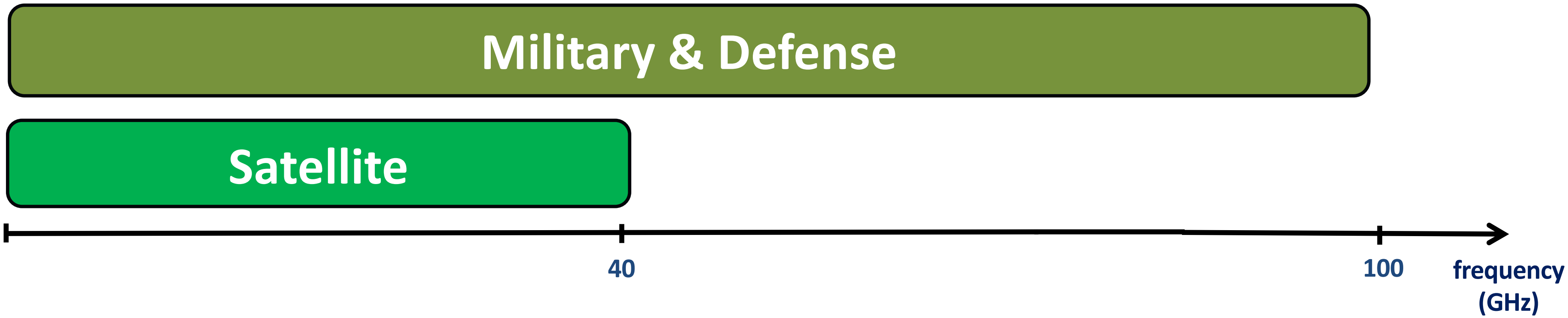
What are the characteristics of systems for wireless communications ?

- **2 – Very high frequency of operation, typically 0,1 - 100 GHz = RF (Radio-Frequency)**

  For specific applications …

  – Satellite communications : from 1 to 40 GHz approximately (discontinued spectrum)

  – Military & Defense communications : from 1 to 100 GHz approximately (exact frequency bands and related applications are kept secret !!!)



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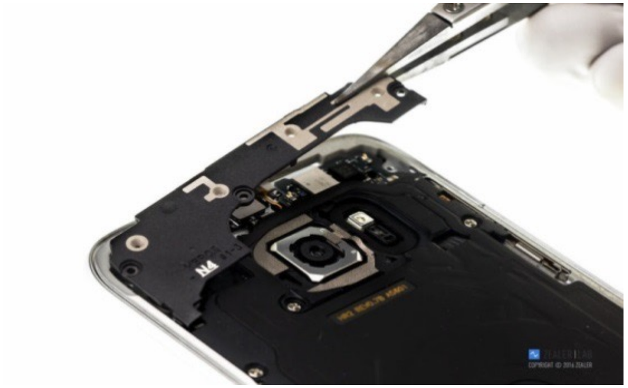
What are the characteristics of systems for wireless communications ?

- 2 – Very high frequency of operation, typically 0,1 - 100 GHz = RF (Radio-Frequency)
  - Why do we use RF frequencies ?

– Size of antennas varies in 1/f ➡ easier integration

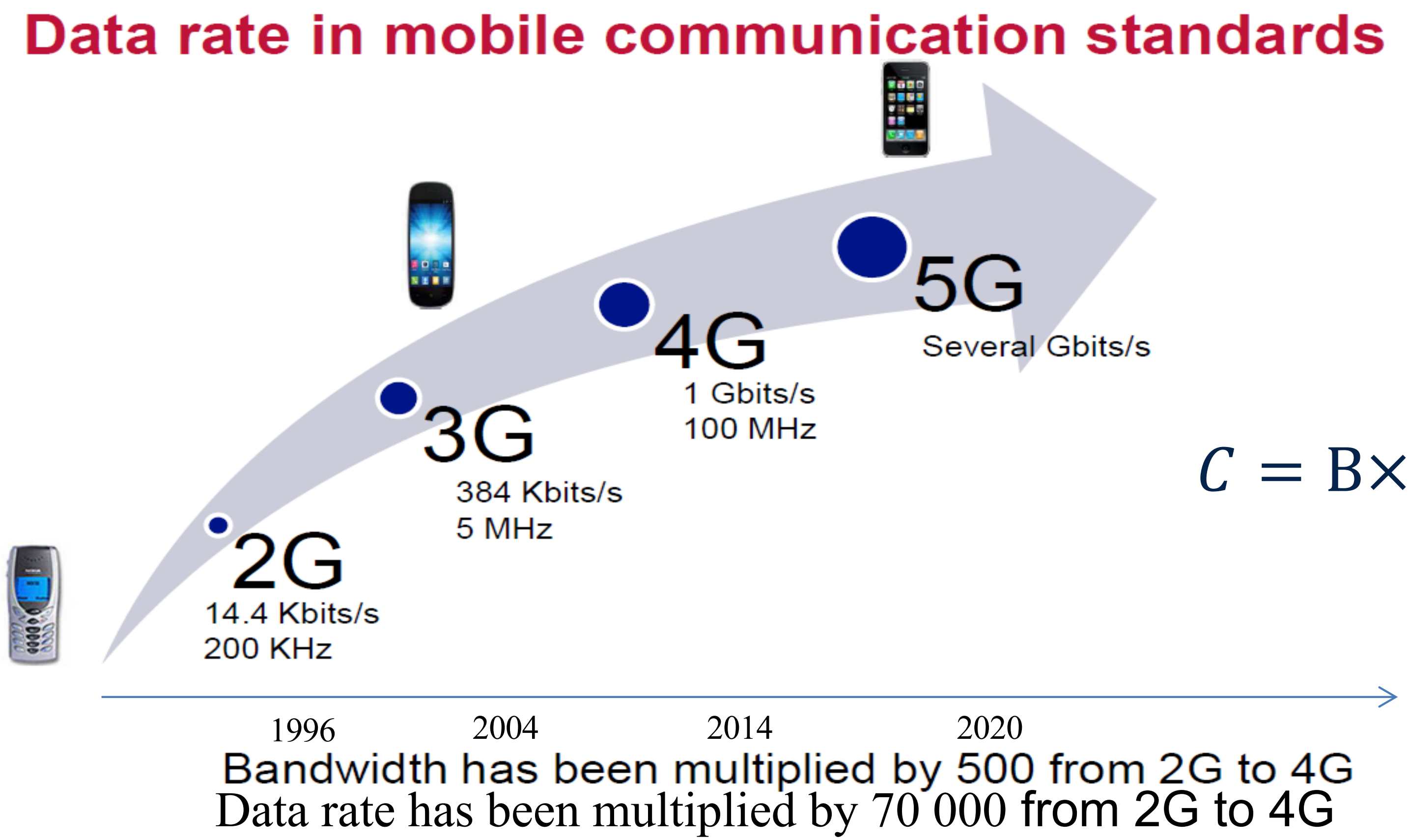


– Favorable propagation conditions (acceptable attenuation in the air, good penetration in buildings, vehicles, weakly dependent on weather conditions, …)

– Availability of wide bandwidths at RF frequencies ➡ high data rates

What are the characteristics of systems for wireless communications ?

- Demand for always higher data rates (especially in mobile communications) but…



$$C = B \times \log_2\left(1 + \frac{S}{N}\right)$$

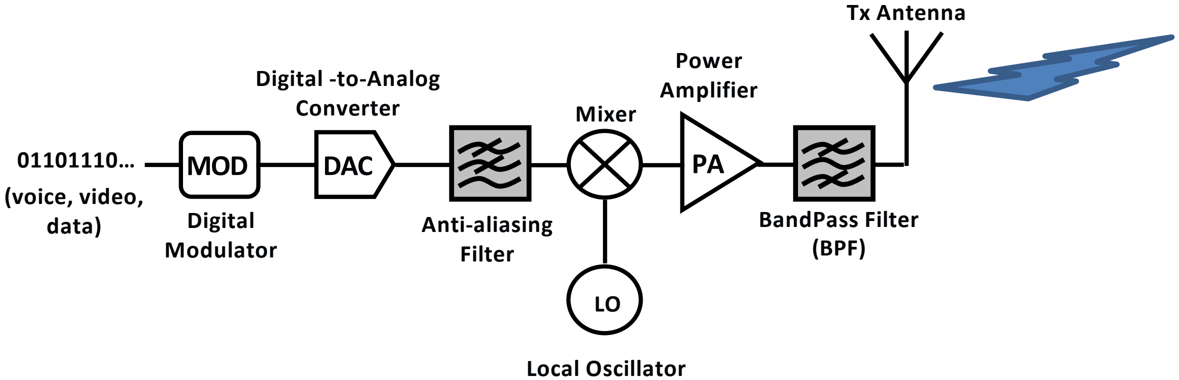
…frequency spectrum is a scarce resource (spectrum < 6 GHz almost fully used)

➡ Present & future trends = research & development at frequencies > 6 GHz & millimeter-wave frequencies (> 30 GHz)

What are the characteristics of systems for wireless communications ?

3 – Electronics circuits for transmission/reception (Tx/Rx) of data

Block diagram of a typical transmitter (Tx)



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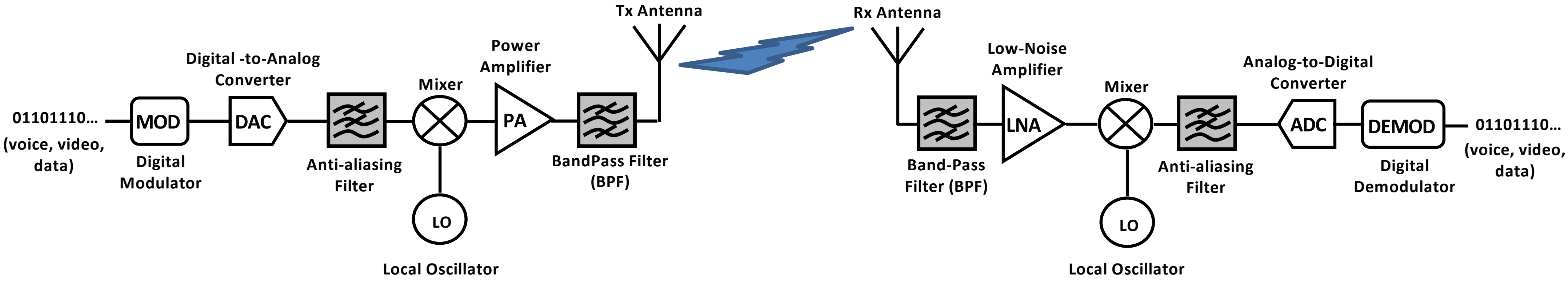
What are the characteristics of systems for wireless communications ?

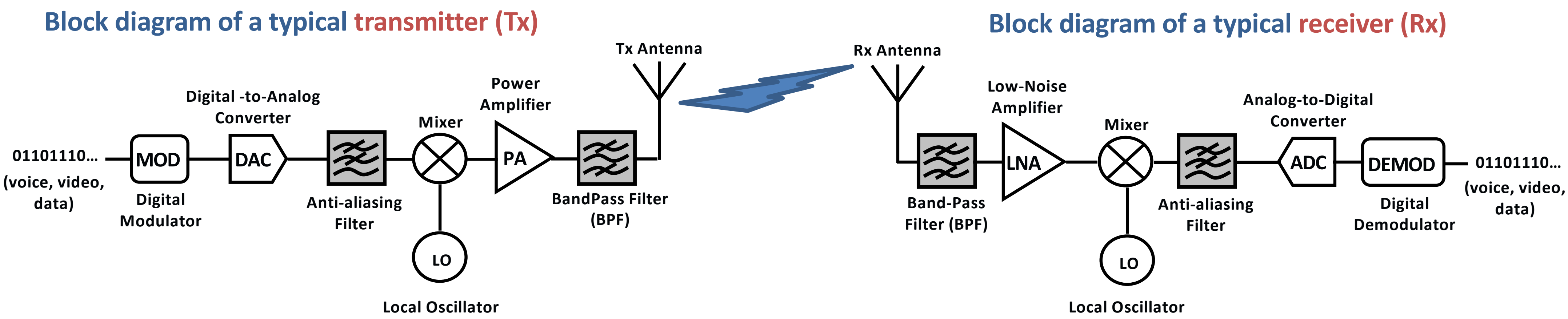
3 – Electronics circuits for transmission/reception (Tx/Rx) of data

Block diagram of a typical transmitter (Tx) **Block diagram of a typical receiver (Rx)**



What are the characteristics of systems for wireless communications ?

3 – Electronics circuits for transmission/reception (Tx/Rx) of data



– Simplified Tx & Rx block diagrams ⇨ Only main RF & BB functions are represented

– Practical Tx & Rx ⇨ - Additional filters and amplifiers are included

- Several mixers may be necessary (2 or 3 mixing stages)

- LO signal is most of the time created by a subsystem called Phase-Locked Loop (PLL)

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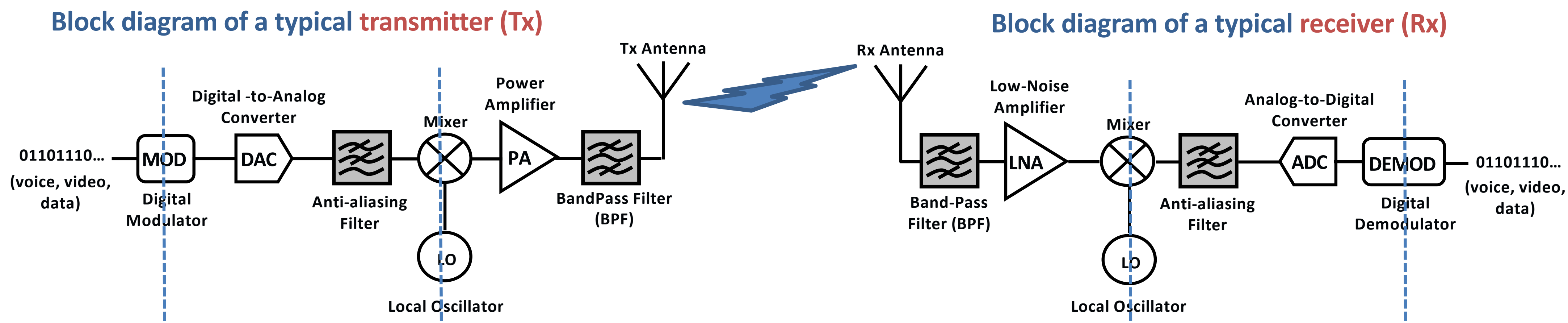
Overview of ICS905 : Analog & RF Functions



- Diplexer, antenna & PA for Front End RF
- BB Filtering
- DAC/ADC
- Digital modulation
- Frequency synthesis
- Transceivers Specifications

Object

- Concepts, architectures and basic components for the front-end RF transceivers.
- Analog blocks : the filters, the amplifiers, the frequency synthesizers and the analog to digital and digital to analog converters (ADC/DAC)

<u>Objectives</u> :

- know the main RF electronics blocks, their operating processes, their main limitations (distortion, noise) and the impact of their performances on the RF channel.
- be able to implement a Phase-Locked Loop, a Filter and a ADC/DAC in a broader context of analog and mixed signal processing.

Program (30h)

- **Basic concepts in RF design and transceiver architectures: P. Desgreys (3h) → 13 sept 8:30**
- **Diplexer, antenna & PA for Front End RF : K. Niotaki (3h) → 20 sept 8:30**
- **Filtering: C. Jabbour (3h) → 27 sept 8:30**
  - **Practical Work : Filtering : C. Jabbour, G.Pham (3h) → 4 oct 8:30**
- **Frequency synthesis: P. Desgreys (1,5h) → 11 oct 10:15**
- **ADC/DAC: P. Desgreys (3h) → 18 oct 8:30**
  - **Practical Work : Delta Sigma ADC: C. Jabbour, G.Pham (3h) → 20 oct 8:30**
- **Transceivers Specifications: C. Jabbour (3h) → 25 oct 8:30**
  - **Practical Work : RF Front-end simulation RF : G. Pham - P. Chollet (3h) → 3 nov 8:30**
- **Elements of communication theory and RF systems : G. Pham (3h) → 8 nov. 8:30**
- FINAL EXAM : 1h30 → **15 nov 10:15**

Validation

- A report must be submitted at the end of each lab session→ 3 grades
- FINAL EXAM : 1h30, with calculator and all the documents → 1 grade

- The final grade is the average between the exam (70%) and the Practical Works (10% each).

- Validation if final grade > 7 (and global average grade of the semester >10)

Futures Trends for
Wireless Communication Systems

Mobile phone evolution

Many technologies
in the terminal

Challenges :
Low cost
Low power

Cellular

Radio et TV

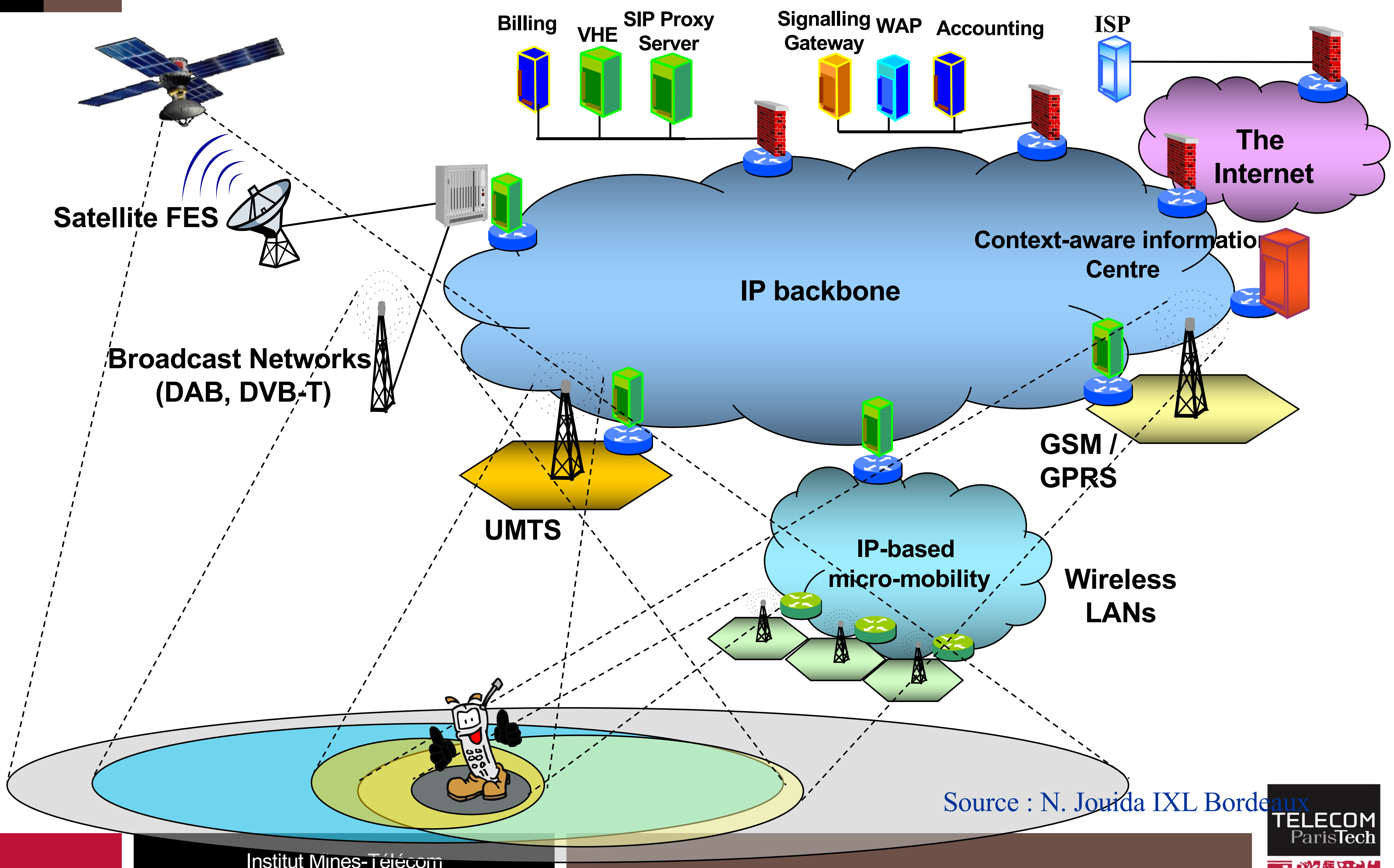
Connectivity

DVB-H : Digital Video Broadcasting Handheld

< 1 billion in 2000
> 6 billions today

Source ST Microelectronics

Network evolution



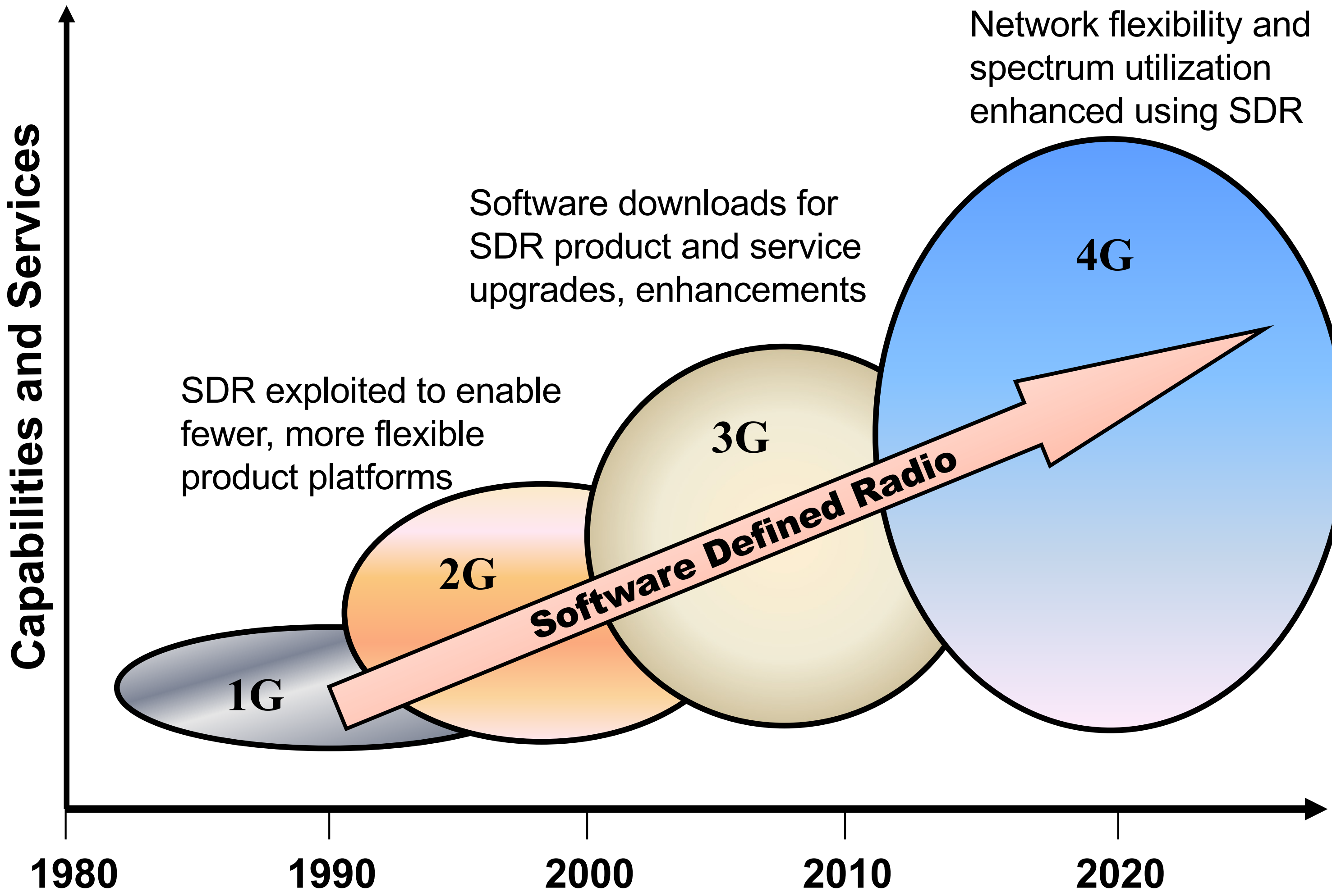
Source : N. Jouida IXL Bordeaux

The software radio

Radio systems : universal, multi usages, multi-standard, multi-band, with reconfigurability for multiply the applications in the future.

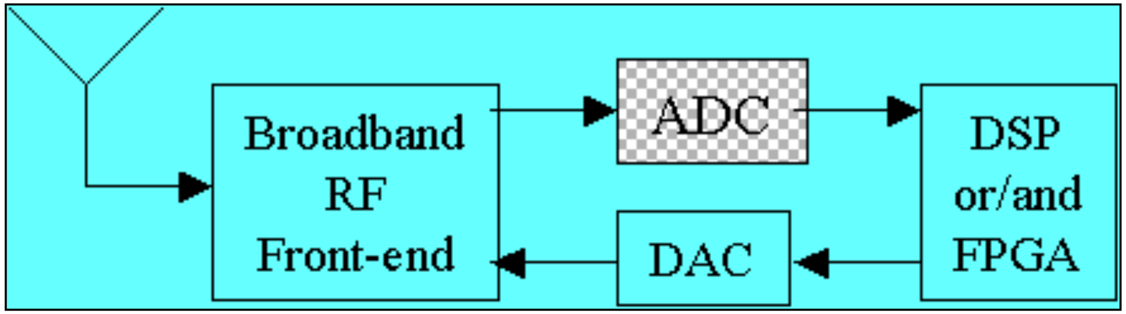
- Reconfigurability by software for base stations and terminals
- « ad hoc » networks

Software defined radio



The radio communication after 2020 ?

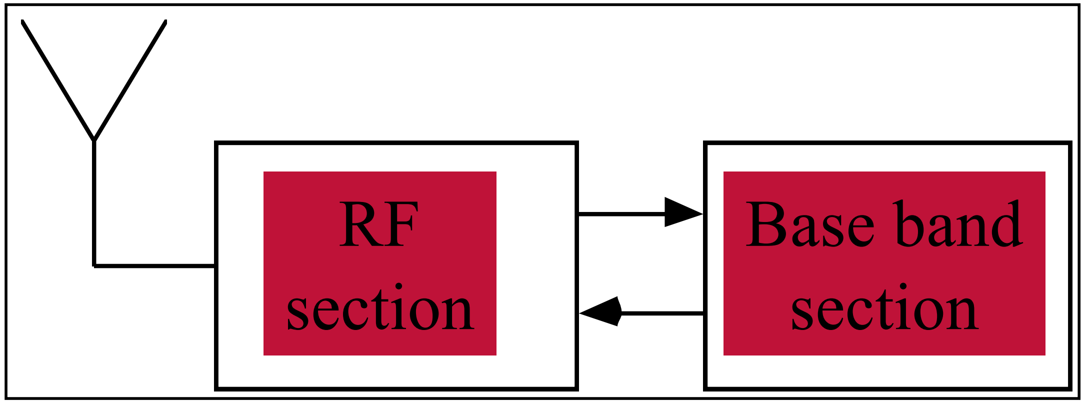
Software radio or
Software defined radio



- ADC :
  - –Carrier frequency > 20 GHz
  - –Signal bandwidth > 1 GHz
  - –Resolution/Linearity : > 15 bits

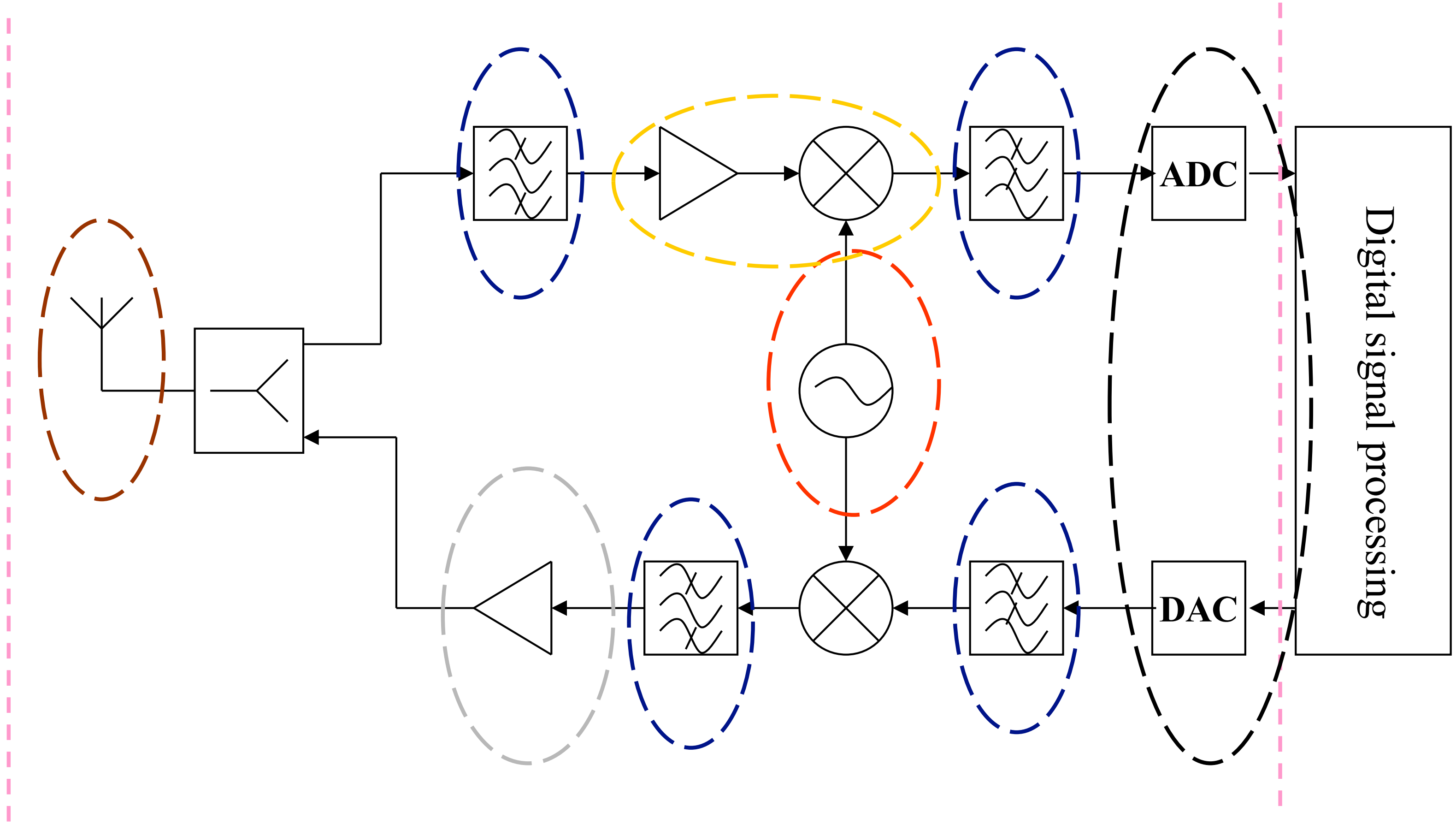
Technological revolution after 2025 ?

RF transmitter evolution



- Mobile phone: One million transistors
- Small part in RF
- RF design is more complicated

Reconfigurability in the RF interface



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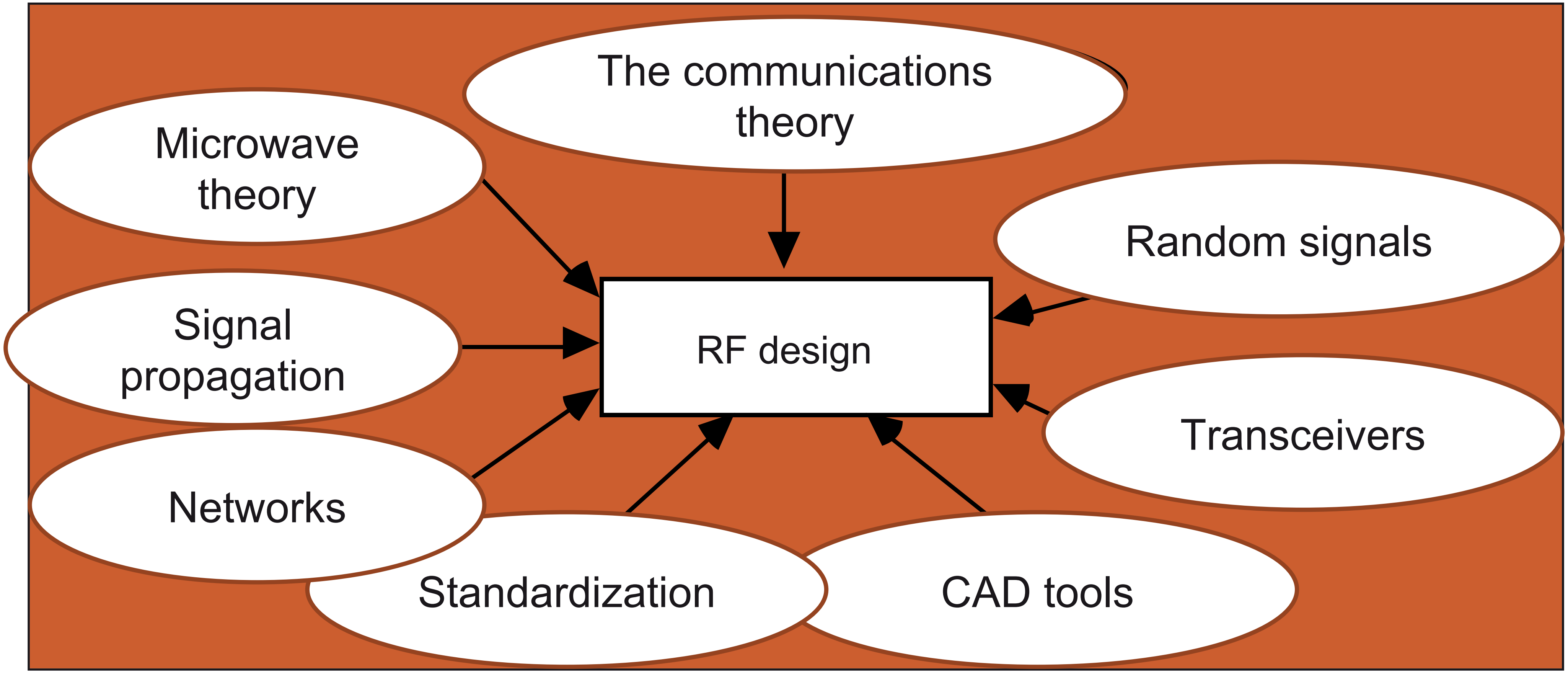
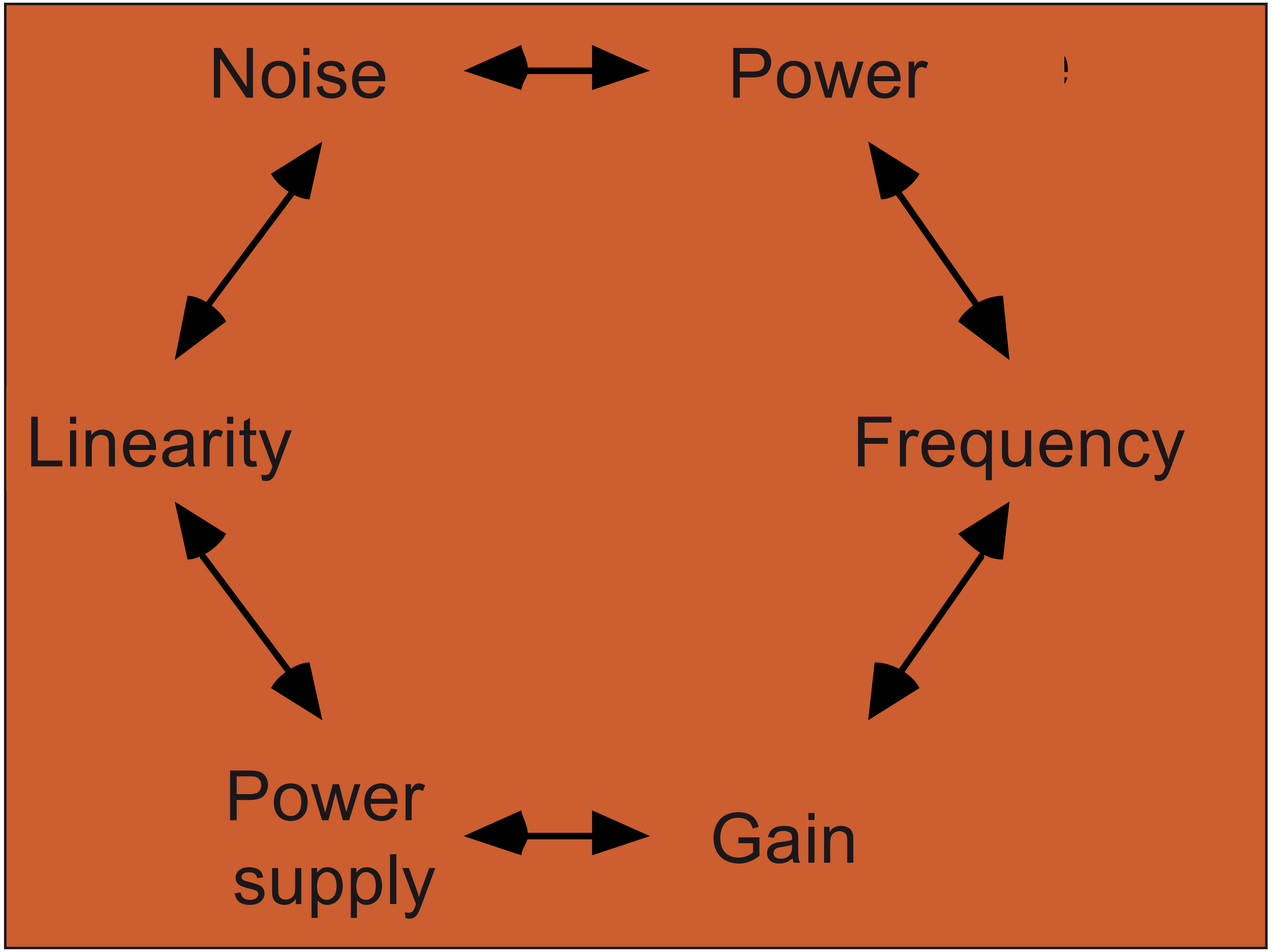
RF design : multi-disciplinary



RF design hexagon



CAD tools

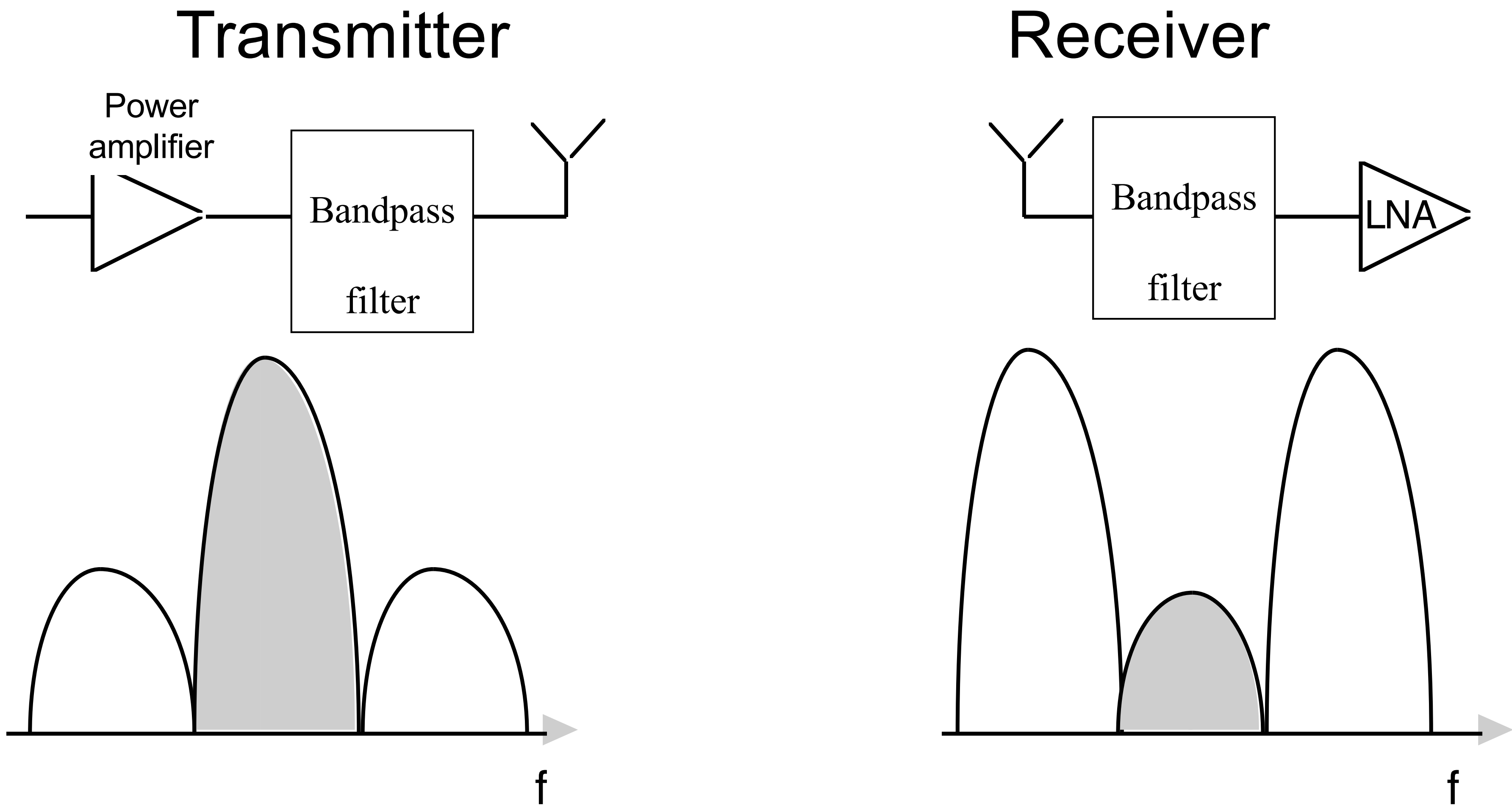
- CAD tools for RF applications : not plug and play
- SPICE : *ac* electrical models linear and invariant in time
- RF : non linear systems, variant in time, noise effects
- Tools today:
  - **Advanced Design System (Electrical simulations), Momentum (Electromagnetic simulator)**
  - VHDL-AMS
  - **CADENCE, Golden Gate**
  - Mentor Graphics
  - **MATLAB**

Technological choices

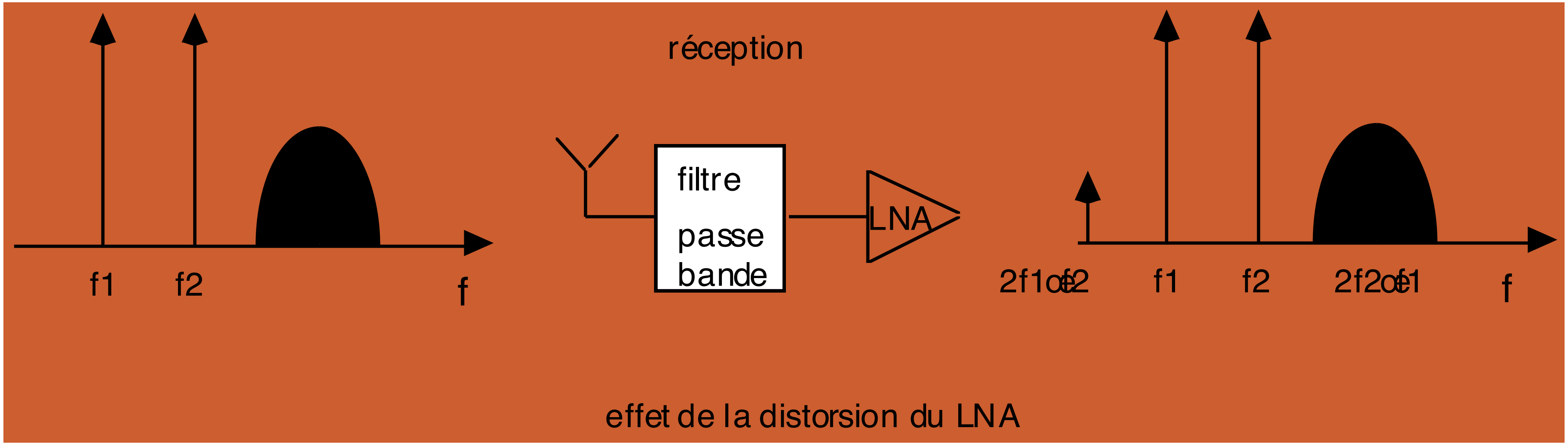
- criteria: performances, cost, market
- Today :
  - AsGa always used for high speed (F_T/F_{max}) and NF : Power amplifier, switches at the antenna level
  - bipolar, **BiCMOS SiGe** used to increase integration and reduce price with still good compromise for speed and noise.
- future : RF-CMOS to lower the price ? Bulk coupling, parameters variability, RF models.

Basic concepts in RF design

Spectrum limited effect



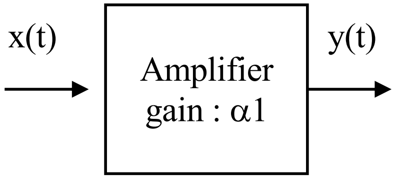
Interference signal effects



The amplifiers non linearities create intermodulation products which can be in the signal band.

Evaluation : Interception order m, IPm.

Non linearity effects in RF



Non linearity effects:

$y(t) = \alpha_1\, x(t) + \alpha_2\, x^2(t) + \alpha_3\, x^3(t).$

If $x(t) = A_1 \cos \omega_1 t$ → harmonics, 1dB compression point

If $x(t) = A_1 \cos \omega_1 t + A_2 \cos \omega_2 t$ then,

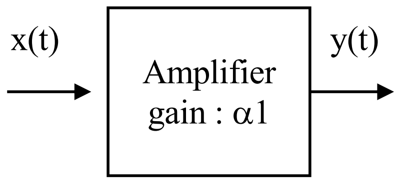
$y(t) = (\alpha_1 A_1 + 3/4\, \alpha_3 A_1^3 + 3/2\, \alpha_3 A_1 A_2^2) \cos \omega_1 t +$

$3/4\, \alpha_3 A_1^2 A_2 \cos (2\omega_1 - \omega_2)t + \ldots..$

2 effects

- Desensitization & Blocking
- Intermodulation

Non linearity effects in RF

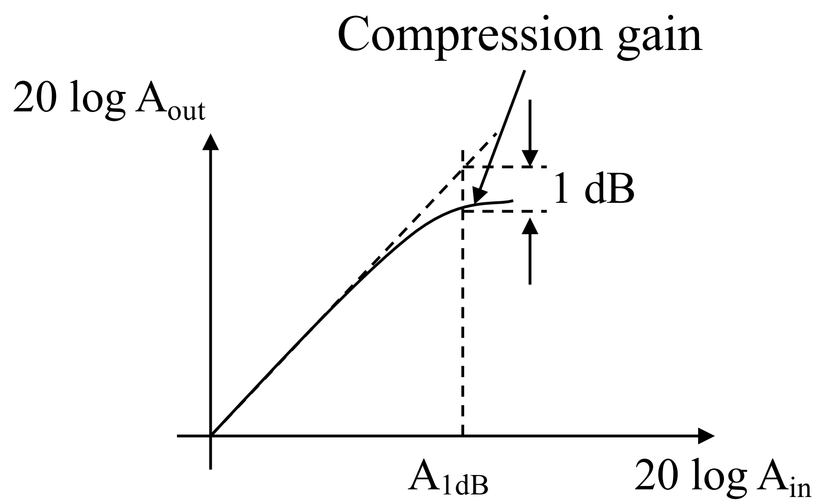


In practice $\alpha_3 < 0$

Non linearity effects:
If $x(t) = A \cos \omega t$ then,

$$y(t) = \alpha_1 A \cos \omega t + \alpha_2 A^2 \cos^2 \omega t + \alpha_3 A^3 \cos^3 \omega t$$

$$y(t) = 1/2\alpha_2 A^2 + (\alpha_1 A + 3/4\, \alpha_3 A^3) \cos \omega t + 1/2\alpha_2 A^2 \cos 2\omega t + 1/4\, \alpha_3 A^3 \cos 3\omega t$$

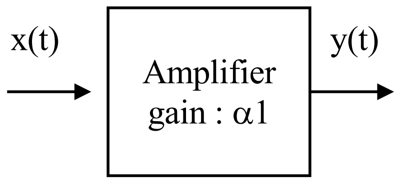


1 dB compression point

$20 \log |\alpha_1 + \tfrac{3}{4} \alpha_3 A^2_{1dB}| = 20 \log |\alpha_1| - 1\text{ dB} \Rightarrow A_{1dB} = (0{,}145\, |\alpha_1/\alpha_3|)^{1/2}$

Typical values for RF amplifier : -25 to -20 dBm, 35,6 to 63,2 mVpp under 50Ω

Non linearity effects in RF



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Non linearity effects:
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$3/4\, \alpha_3 A_1^2 A_2 \cos (2\omega_1 - \omega_2)t + \ldots$..

•Blocking:
ω_1 in band and ω_2 outside, with $A_1 << A_2$.
Blocker amplitude can be 60 to 70 dB above useful signal

• Intermodulation:
ω_1 et ω_2 outside the band
with $A_1 = A_2$.

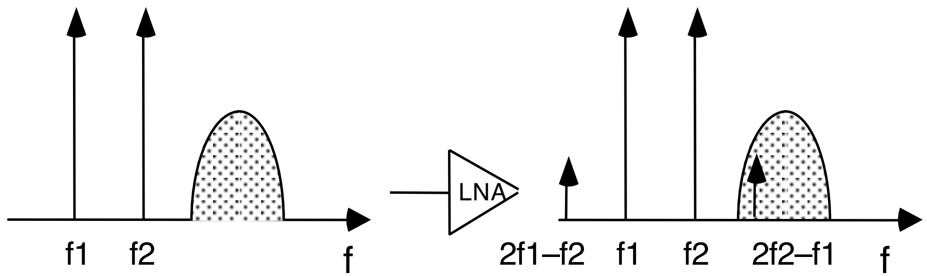
Third interception point: IP3

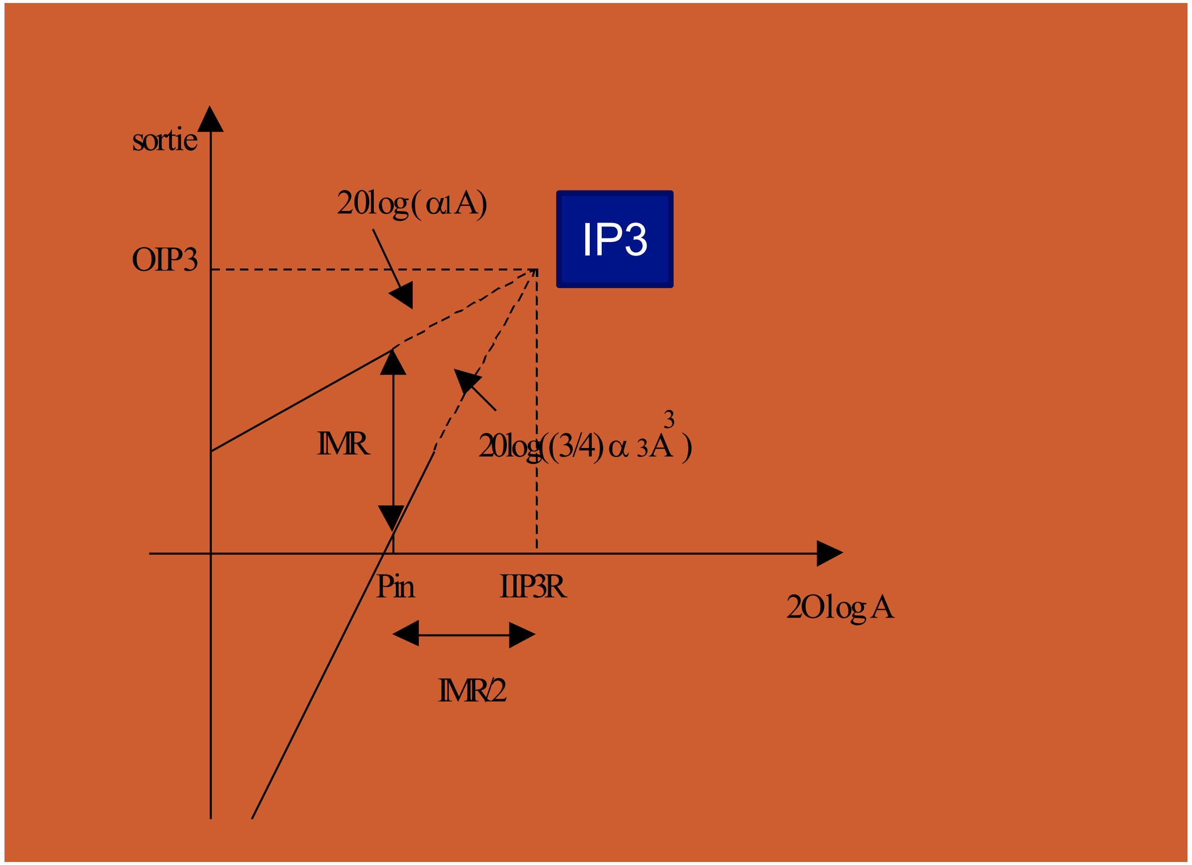
$$y(t) \cong (\alpha_1 A + \ldots) \cos \omega_1 t +$$

$$3/4\ \alpha_3 A^3 \cos(2\omega_1 - \omega_2)t + \ldots..$$

At the receiver input:

$$IIP3 = Pin + 0,5\ IMR$$





Signal and noise

- Noise Figure :

$$F = SNR_{input} / SNR_{output}$$

- Noise Figure in dB :

$$NF = 10 \log_{10} F$$

- Sensitivity : weakest RF signal power that can be processed to develop a minimum signal-to-noise ratio for achieving a required bit error rate (BER)

- Dynamic range : ratio between signal max and signal min

Noise Figure

- **Given an amplifier block of gain G so that :**
  - $S_o = G\, S_i$;
  - **Noise factor : $F = SNR_i / SNR_o$** $= (S_i/N_{i\,(source)})/(S_o/N_{o\,(total)}) = (S_i/N_{i\,(source)})/(G\, S_i/N_{o\,(total)}) =$ $\mathbf{N_{o\,(total)}/G\, N_{i\,(source)}}$;

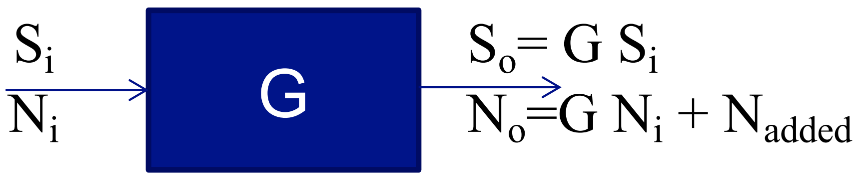
  with $N_{o\,(total)}$ the total noise at the block output.

  We define $N_{o\,(source)}$ the output noise due to the source and $N_{o\,(added)}$ the intrinsic noise of the block so that :

  $N_{o\,(total)} = N_{o\,(source)} + N_{o\,(added)} = G\, N_{i\,(source)} + N_{o\,(added)}$

  $\mathbf{F} = N_{o\,(total)}/G\, N_{i\,(source)} = N_{o\,(total)}/N_{o\,(source)} = (N_{o\,(source)} + N_{o\,(added)})/N_{o\,(source)} = \mathbf{1 + N_{o\,(added)}/GN_{i\,(source)}}$

  - The noise power from a simple load $N_{i\,(source)} = kT_0B$, , where *k* is Boltzmann's constant, T_0 is the standard noise temperature T_0 = 290 K, and *B* is the measurement bandwidth (or the receiver bandwidth)



Friis equation

- **Cascade of several amplifiers:**

$S_o = G_1.G_2\ldots.G_m\ S_i$; the added noise by each block j is represented by $N_{j\ (added)}$;

so the total noise at the chain output is given by :

$N_{o\ (total)} = N_{i\ (source)}.G_1.G_2\ldots.G_m + N_{1\ (added)}\ G_2\ldots.G_m \ldots. + N_{m\ (added)}$;

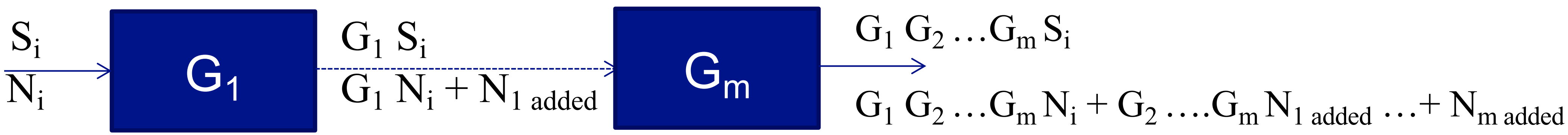
With $N_{o\ (source)} = N_{i\ (source)}\ G_1.G_2\ldots.G_m$;

$\mathbf{F = N_{o\ (total)}/N_{o\ (source)}} = 1 + (N_{1\ (added)}/G_1N_{i\ (source)}) + (N_{2\ (added)}/\ G_1.G_2\,N_{i\ (source)}) + \ldots.\ N_{m\ (added)}/\ G_1.G_2\ldots.G_m\,N_{i\ (source)})$

Now for each block j : $F_j = 1 + N_{j(added)}/G_jN_{i\ (source)}$ or $F_j - 1 = N_{j(added)}/G_jN_{i\ (source)}$.

By replacing in the above equation, the Friis equation is demonstrated :

$$\boxed{F = 1 + (F_1 - 1) + (F_2 - 1)/G_1 + \ldots..\ (F_m - 1)/\ G_1.G_2\ldots.G_{m-1}}$$

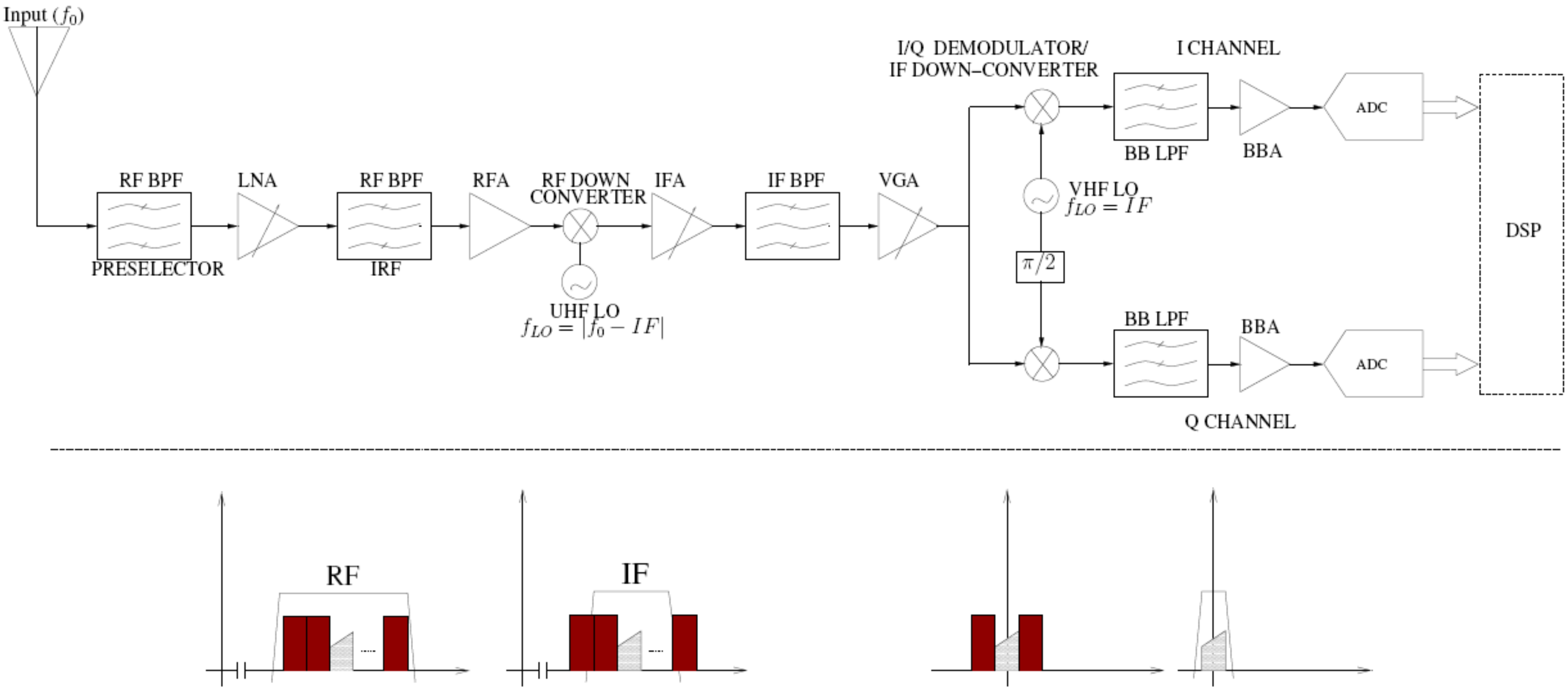


Transceiver architectures

Architecture choice

- complexity
- cost
- Power consumption
- Number of external components

Superheterodyne receiver



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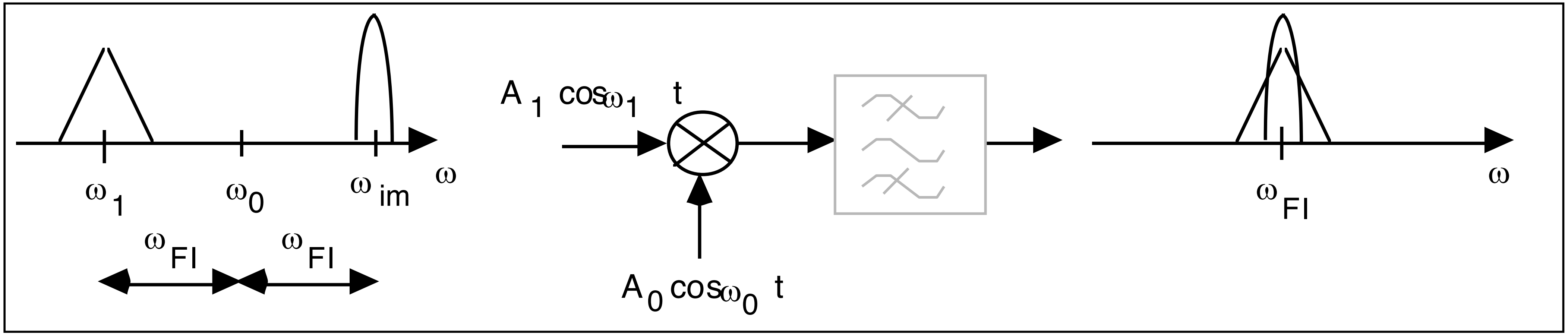
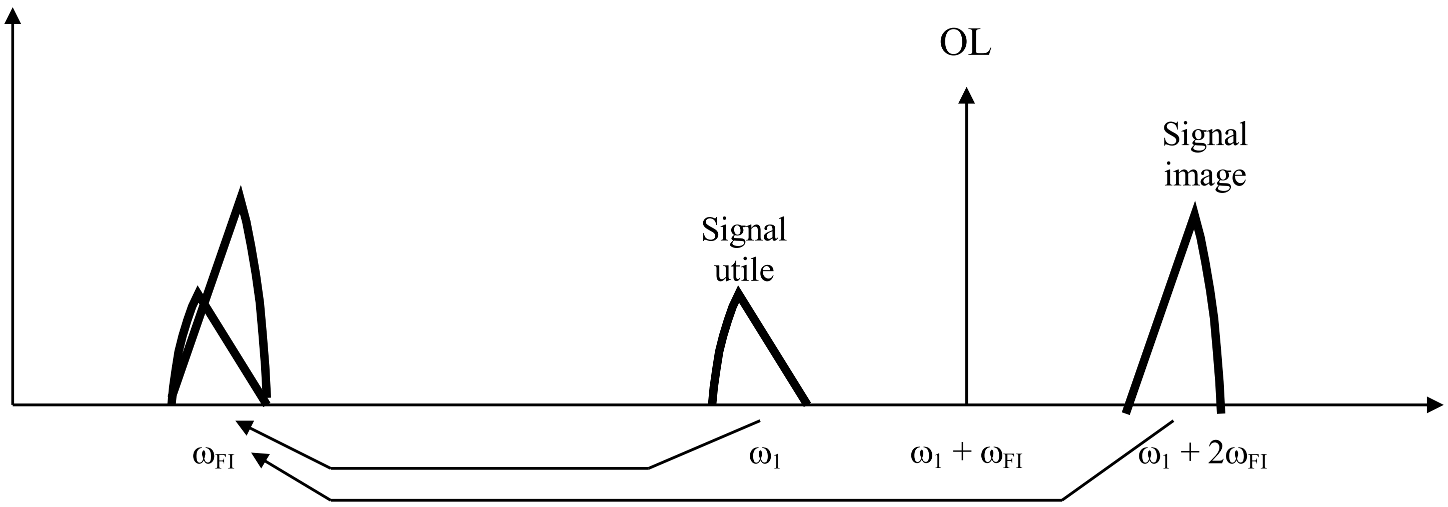
Mixer effects : Image frequency





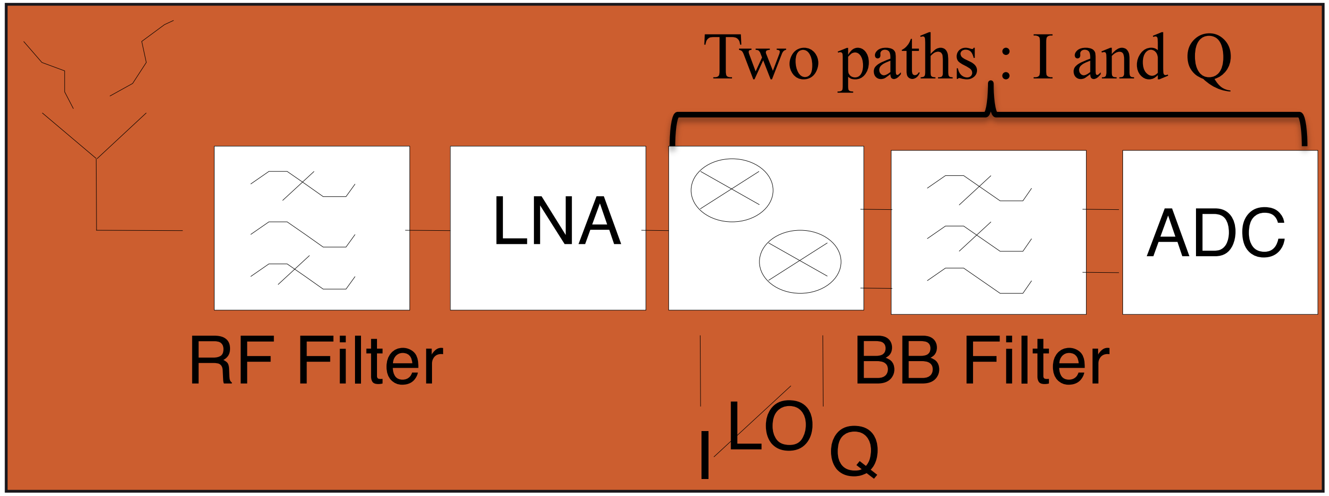
Design consideration of superheterodyne receiver

- **Sensitivity**
  - minimum detectable desired signal to obtain a certain bit error rate (BER)
  - Determined by noise figure of the receiver and processing gain
- **Linearity**
  - IP3 or IIP3 (input third-order intercept point)
- **Selectivity**
  - Mainly determined by RF, IF and BB filters
  - Suppress the interference from adjacent channels and others sources
  - To be broad enough to pass the desired signal
- **NF and IP3 are dependent on the gain distribution**
  - Lower noise figure and high sensitivity for the front-end blocks : antenna → LNA→ Mixer
  - High front-end gain degrades the receiver linearity
  - **Gain distribution : tradeoff between NF and linearity**

Dynamic range and AGC (Automatic Gain Control) systems

- **The highest received signal level : from -25 dBm to -20 dBm**
- **Dynamic range: from 80 dB to 85 dB**
- **Receiver AGC**
  - The AGC reduces receiver total gain for strong signals and increases gain for weak signals.
  - Temperature effects, inaccuracy of gain…
  - Maximum gain of the receiver chain: the ADC max input level
  - Control accuracy of the receiver AGC: ± 2 to ± 2.5 dB
  - Time constant of the receiver AGC: around 2 ms

Direct-Conversion (zero IF) architecture



- No image problem
- IF passive SAW filter eliminated: cost and size reduced
- Channel filtering: analog base band by means of active low-pass filter
- Bandwidth of the active filter: adjustable → multimode operation with a common analog base-band circuitry

Direct-Conversion (zero IF) architecture

- **Idea introduced in 1924**
- **Very difficult to implement on discreted circuits**
- **RF IC design tools make it possible**
- **GSM mobile stations in 1990s**
- **DC offset caused by:**
  - LO self-mixing
  - Transmission leakage self-mixing
    - From the duplexer, RF port and LO port of the mixer
    - From PA through the substrate/printed circuit board
- **DC offset values**
  - The gain in BB: 70 to 80 dB
  - 200 to 250 μV DC offset saturates the last stage

Direct-Conversion (zero IF) architecture

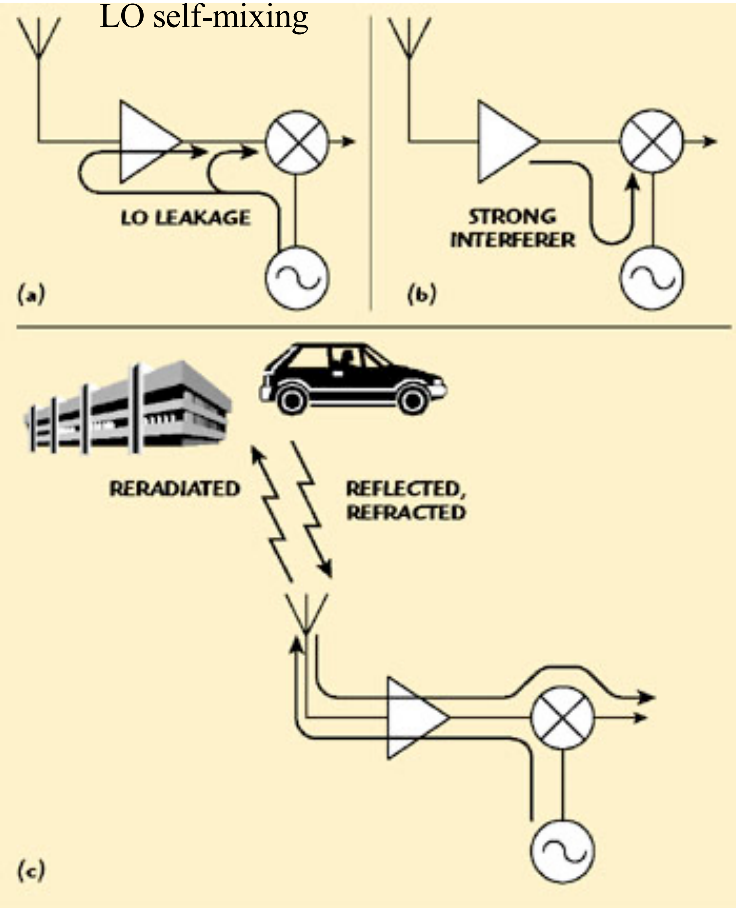


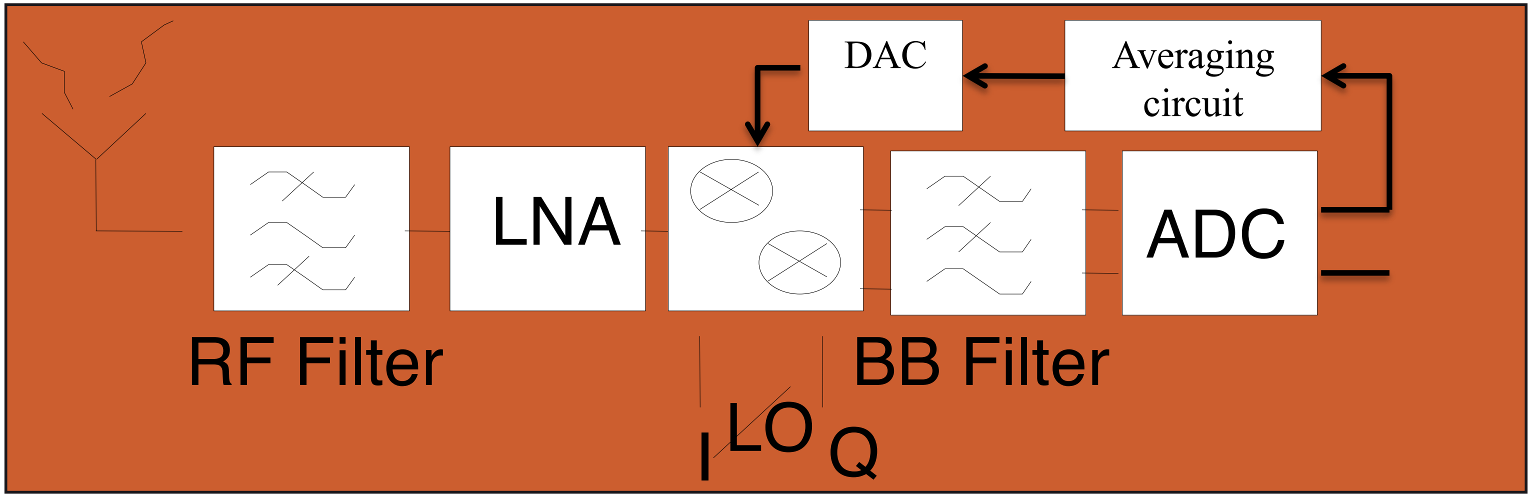
Fig. 8 DC offset mechanisms.

- Second-order nonlinearity becomes critical : IP2
- RF filter rejects the transmission leakage to relax the IP2 constraints
- Various phenomena contribute to the creation of DCs.

On the Direct Conversion Receiver -- A Tutorial-A detailed look at the characteristics of the direct conversion receiver
Ashkan Mashhour, William Domino, Norman Beamish, Microwave Journal, 2001

Direct-Conversion (zero IF) architecture

- **DC offset cancellation**
  - High-pass filter around the DC
  - Time-invariant DC offsets calibrated in different gain modes and stored as a look-up table in a memory and subtracted in the analog BB through a DAC
  - Time-variant DC offset measured by averaging and subtracted in the analog BB through a DAC



Direct-Conversion (zero IF) architecture

- **Second-order distortion : IP2**
  - If first RF blocks (up to the mixer) output is as following:

    $y(t) = a_1\, x(t) + a_2\, x^2(t) + \ldots$
  - If the input is made of two strong narrow-band interferers:

    $x(t) = A \cos 2\pi f_a t + B \cos 2\pi f_b t$
  - The second order nonlinearity generates low-frequency products:

  $a_2\,(A \cos 2\pi f_a t + B \cos 2\pi f_b t)^2 =$

  $a_2(A^2 + B^2)/2 + a_2 AB \cos 2\pi(f_a - f_b)\, t$ + high frequency components

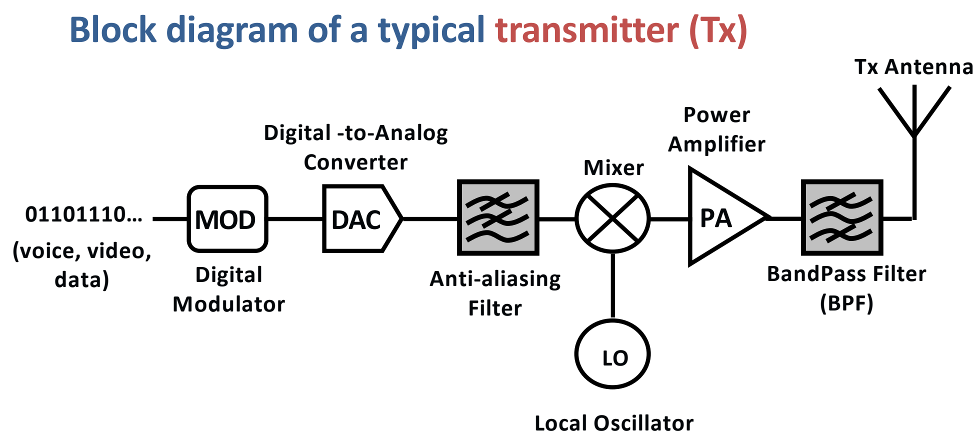
- **To minimize the impact of the second-order distortion**
  - Mixer with very high IIP2 greater than + 55 dBm.

Direct-Conversion (zero IF) architecture

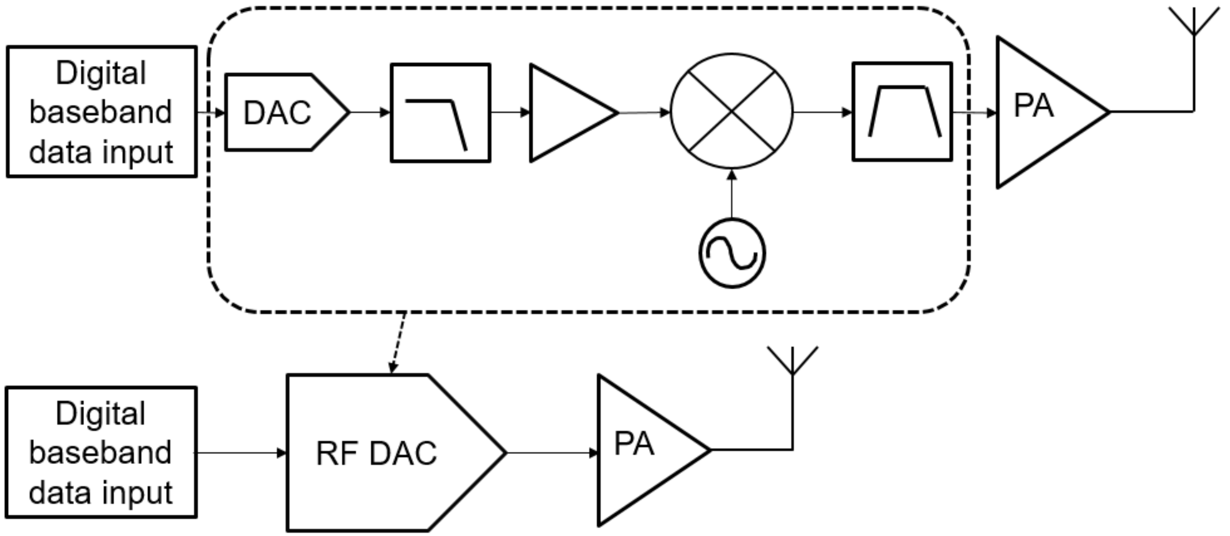
- I/Q mismatch : BB signals, I and Q, should have their 90° phase offset well matched as much as possible
- 75% of the overall receiver gain is obtained from the analog base-band block
- Channel selectivity depends on the stop-band rejection of the low-pass filter
- I and Q channels are converted into digital signals by ADC
- Digital filters suppress nearby interferers and enhance the channel selectivity

Transmitter architecture

- **Direct conversion :**
  - Impulse form
  - DAC
  - RF modulation
- **2 steps for transmit the signal**
  - Intermediate frequency

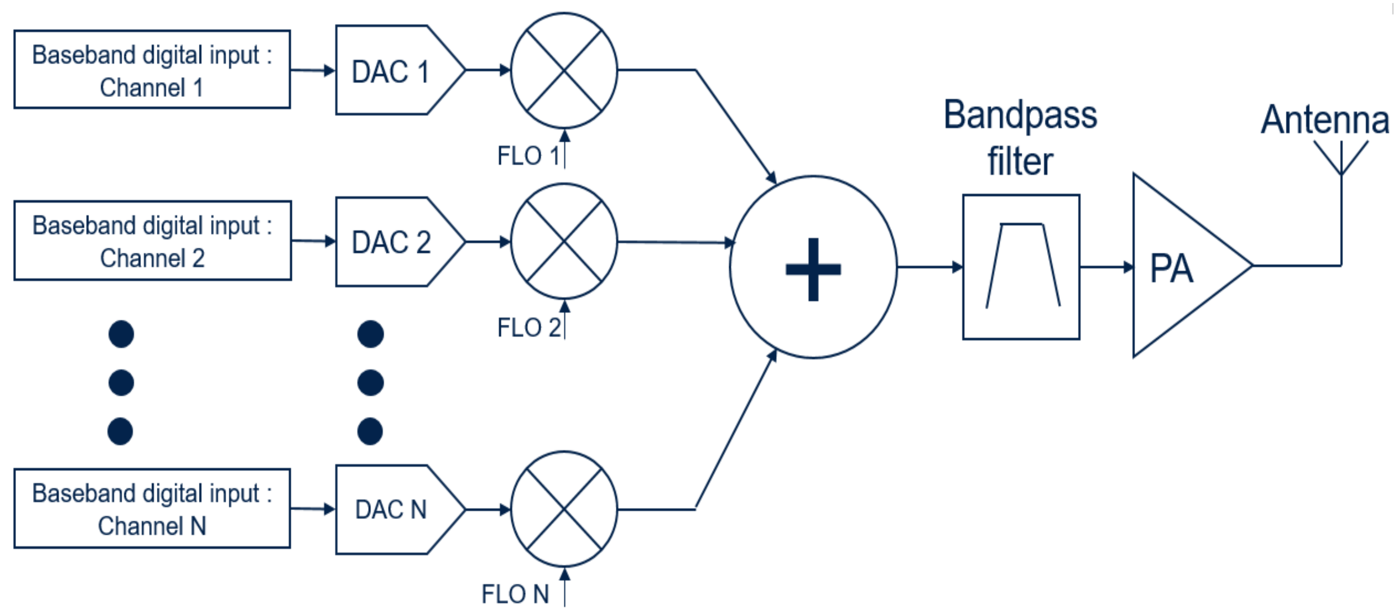


Transmitter architecture



Block diagram of a transmission link, with a classic architecture, and Direct RFDAC architecture

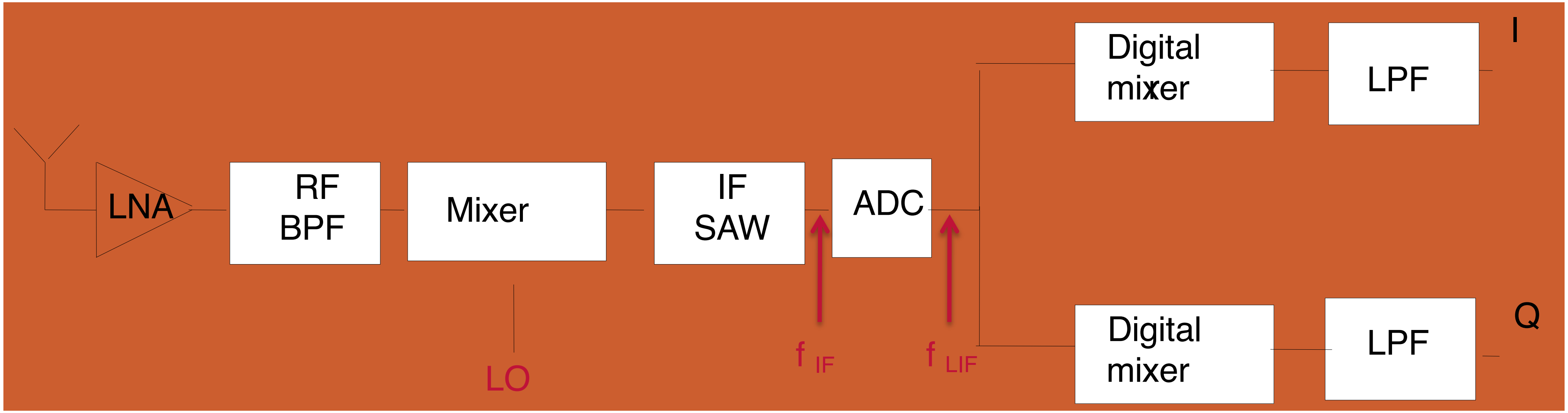
Transmitter architecture



traditional wideband transmission system implementation

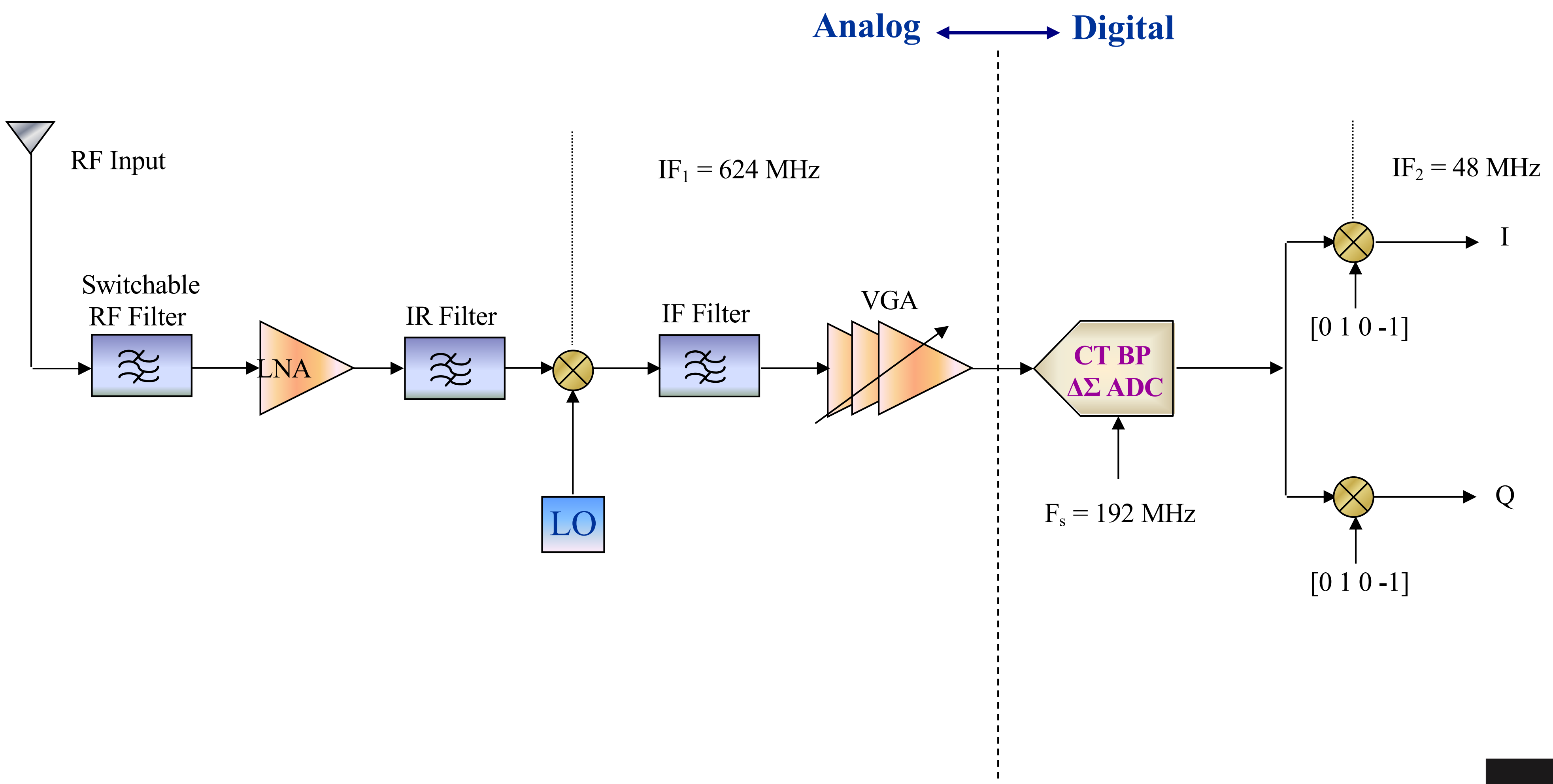
Design examples

Undersampling receiver

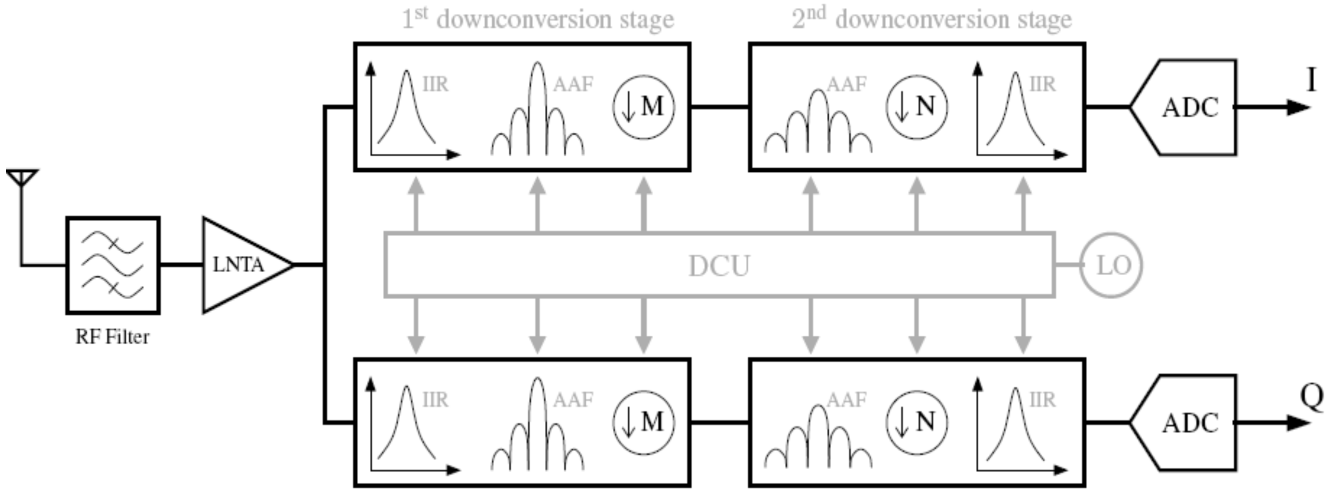


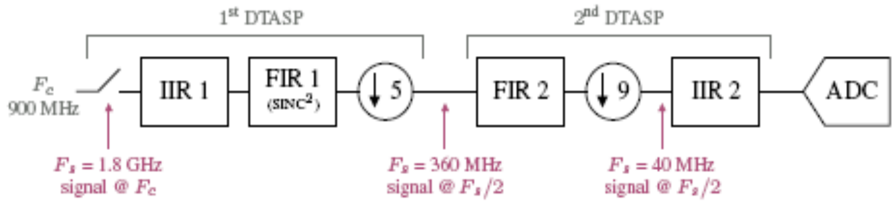
- ADC band-pass ΔΣ can be used
- The second mixer is digital
- Band-pass sampling is used for undersampling RF signals and more often for undersampling IF signals

Digital Intermediate frequency

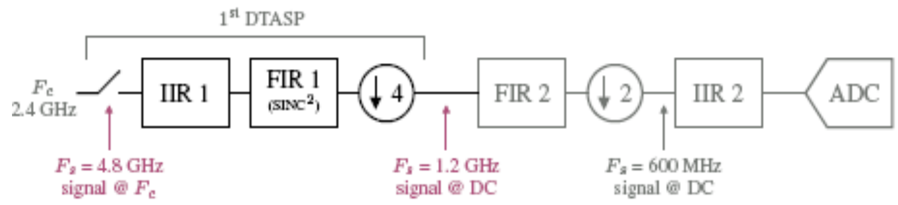


Discrete time RF receiver for multistandards





GSM mode



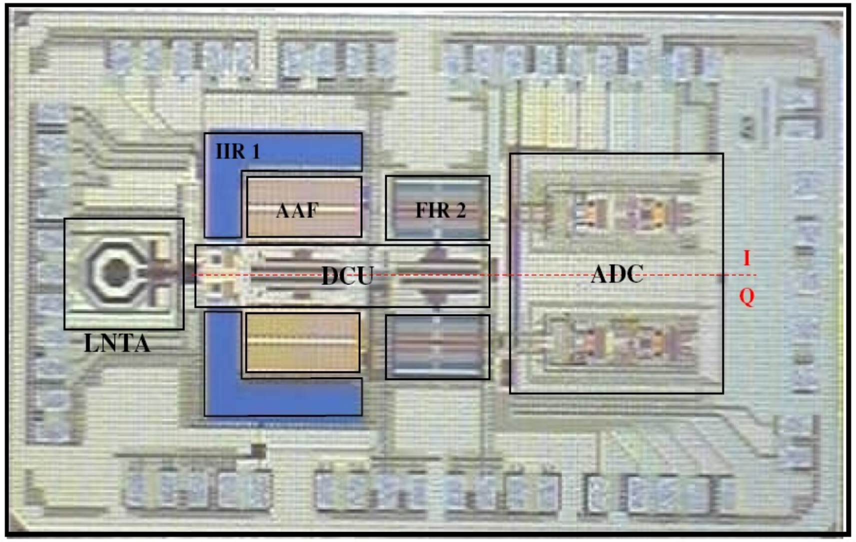
WiFi mode

Major contributions :

- Efficiency of anti-aliasing filter (alias rejection) ⇒ second order (**Sinc²**)
- **High pass** sigma delta ADC
  - **Inherently cancel Dc offset, flicker noise and significantly reduce second order intermodulation**
- **Versatile ADC** : for narrow band (GSM/EDGE) and Wide band (WiFi/WiMax)
  - **Combining sigma delta modulation and time-interleaving**

Design examples

- Discrete time RF receiver for GSM and Wifi (2008)
  - Technology : 90nm CMOS
  - Narrowband and wide band
  - Sinc² anti-aliasing filters
  - High-pass sigma delta ADC

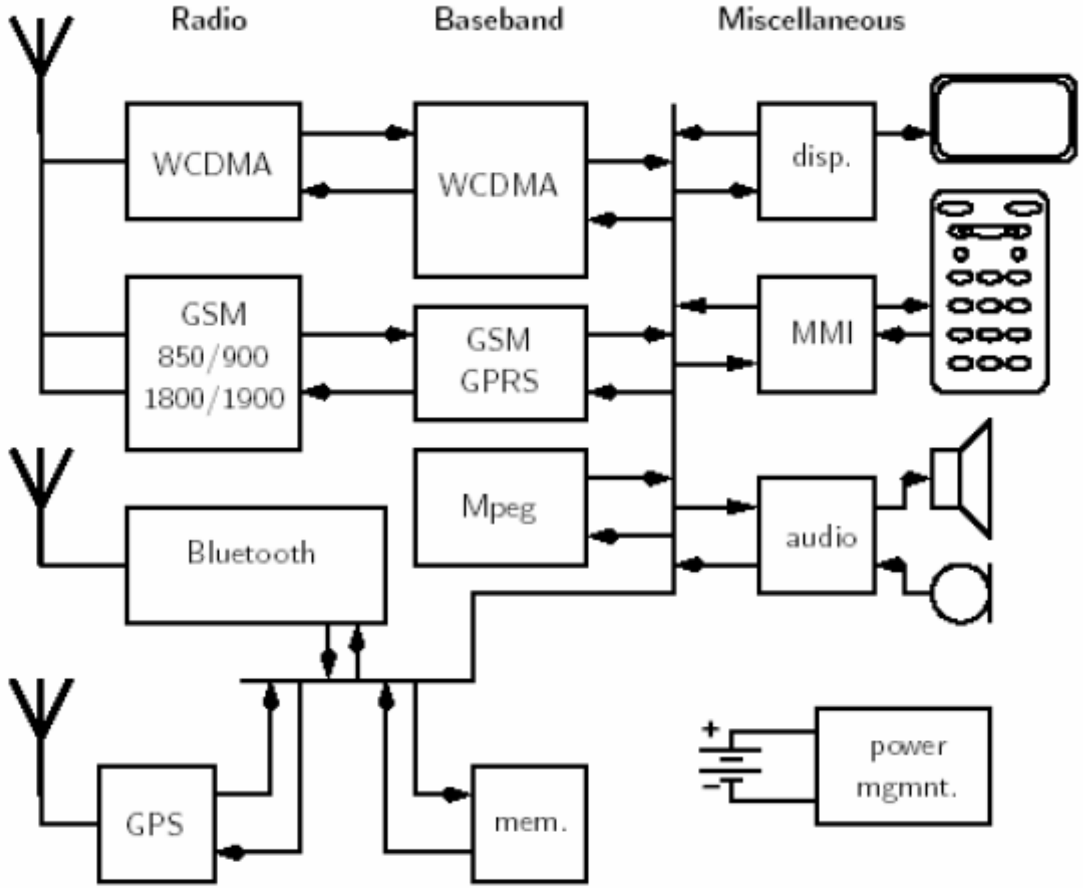


http://pastel.enst.fr/view/people/Latiri,_Anis.html

multistandard architecture

Hand-set features

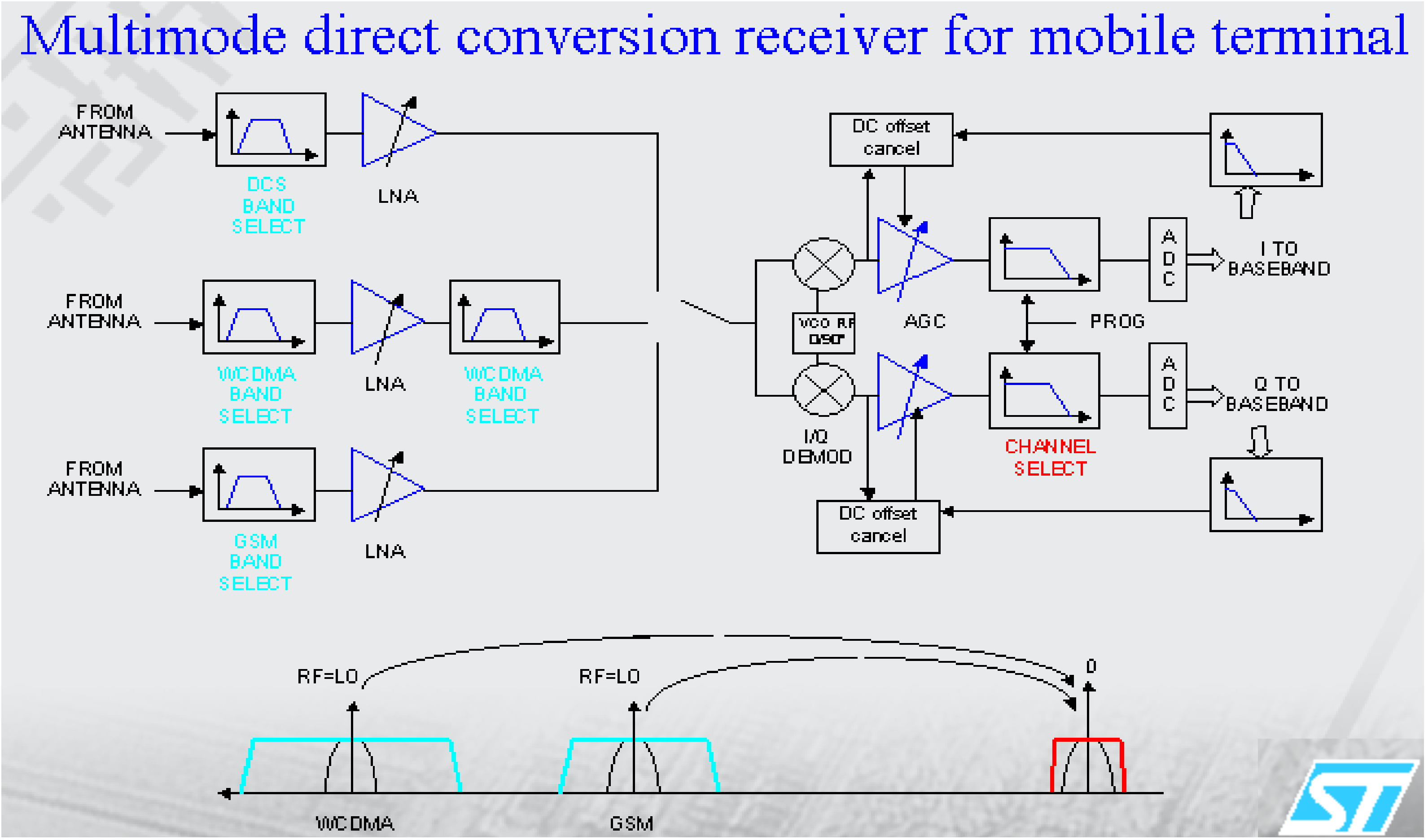
- multi-band
- multi-standard
- low-end & high-end
- IP reuse



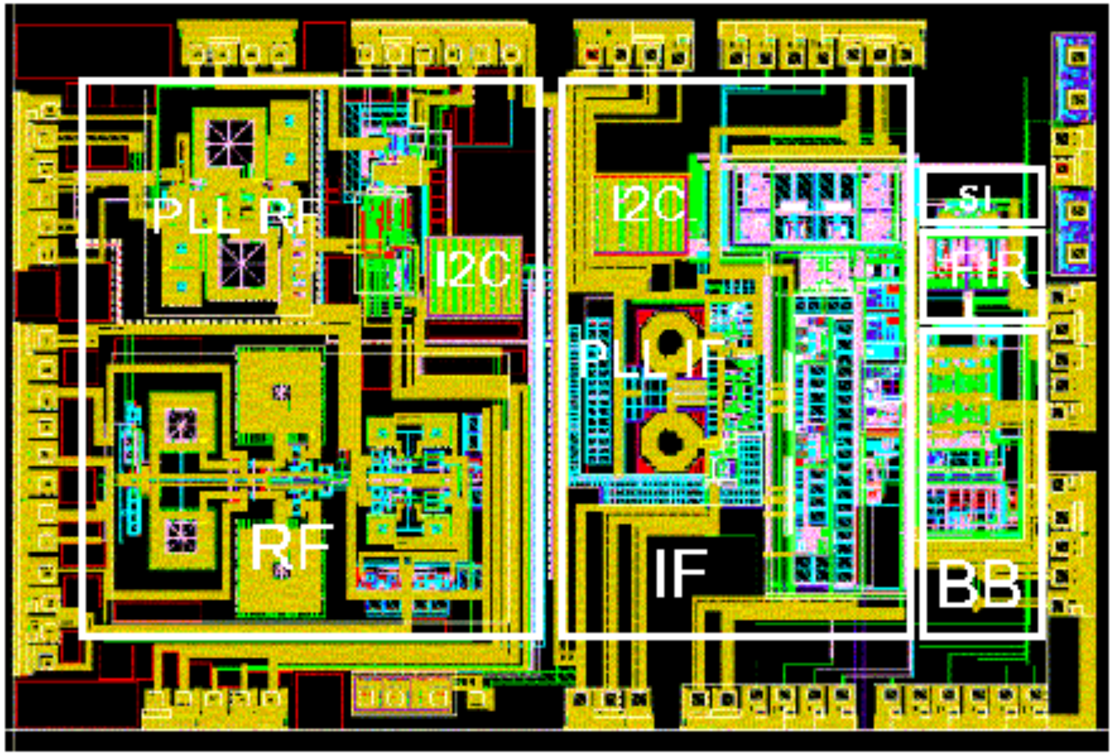
TELECOM ParisTech

Multimode example

Multistandard Equipment



GSM / DCS Receiver



Size : 6300 x 3700 um   Package: TQFP100 Slug Down

Source ST Microelectronics

RF circuit evolution

S888 ⇝ R520

S888

1997

Same scale!

Sony Ericsson R520 GSM Cell Phone

R520

GSM, GPRS, Bluetooth

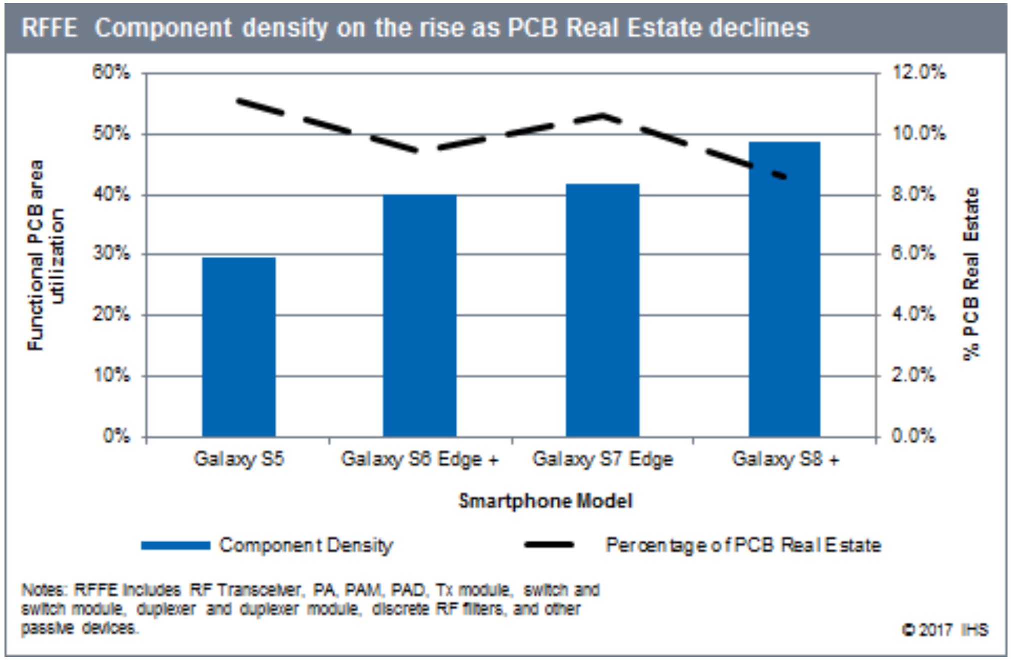
RFFE complexity has increased with every generation of WWAN technology

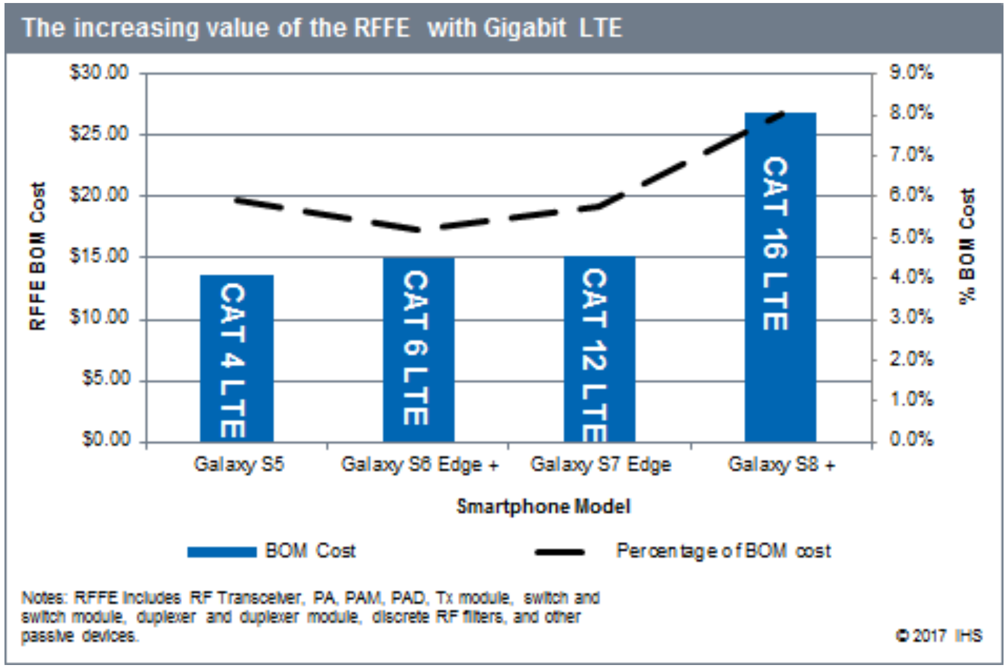
- ↗ Increasing complexity in the RFFE: number of transmit and receive paths present in a device.

- Cat16 LTE delivers downlink speeds of around one gigabit per second (1Gbps) thanks to:
- 4x4 multiple-input-multiple-output (MIMO) antenna architectures
- Carrier aggregation

- biggest impacts → RF components in the receive chain
- through increasing filtering and switching content which may be combined into modules with other content such as LNAs

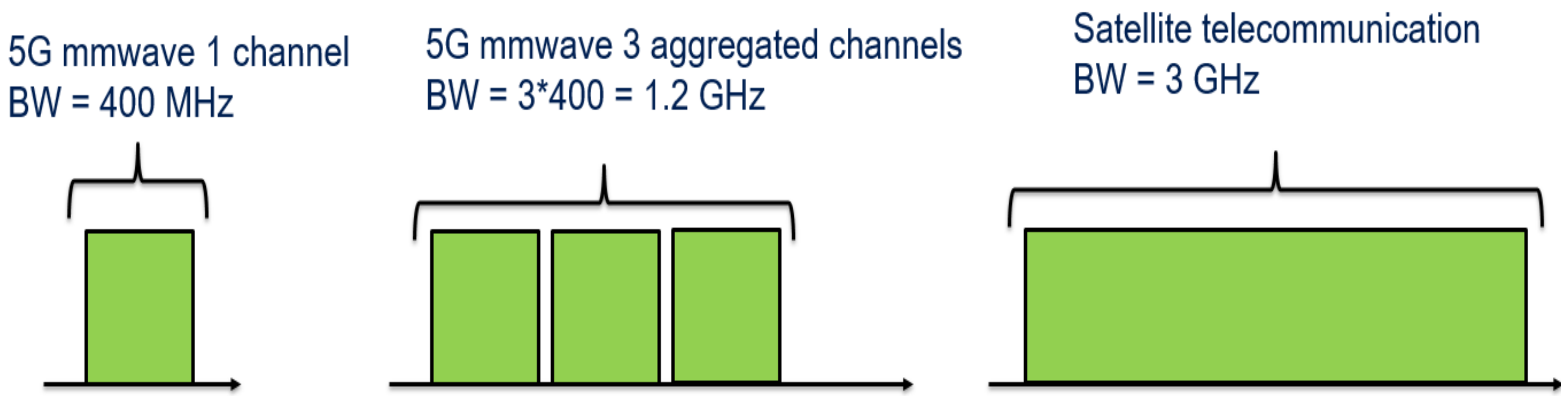
RFFE complexity has increased with every generation of WWAN technology





more components and added cost from the RFFE

Carrier aggregation



5G mmWaves channel, aggregation of channels and Satellite telecommunication channel

Bipolar LNA

- Ze = rb + gmLe/Cπ + Lep +1/Cπp

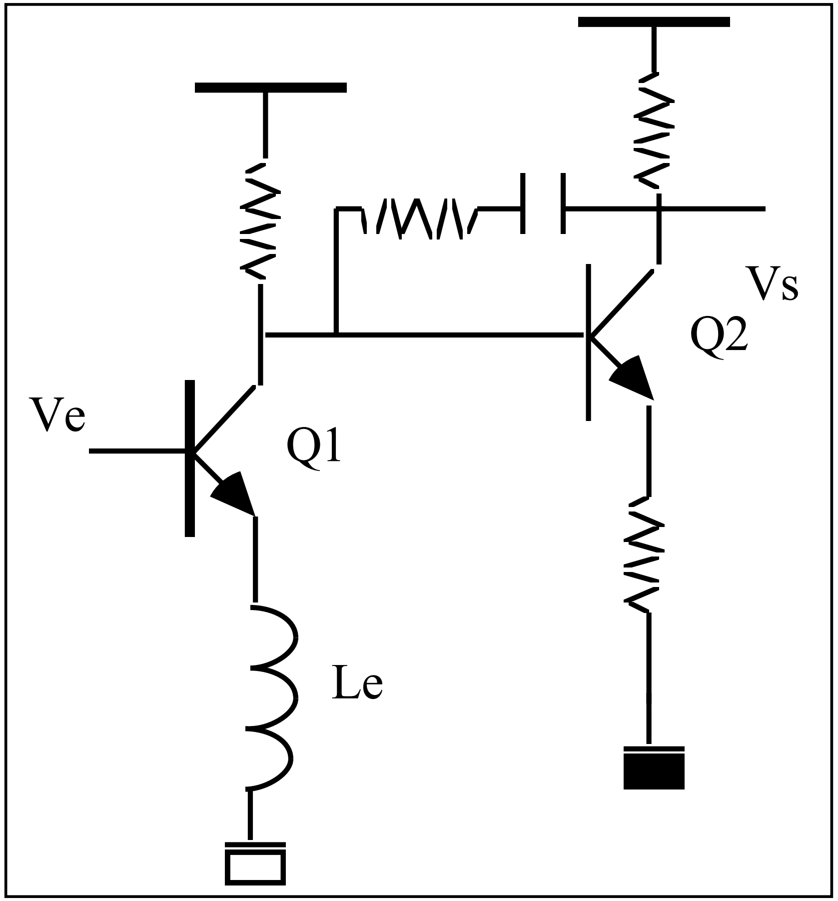
rb + gmLe/Cπ = 50 Ω

- BiCMOS 13 GHz alim 5V :

NF = 2,2 dB

IIP3 = –10 dBm

gain = 16 dB à 900 MHz



LNA CMOS

- CMOS more linear than Bipolar in RF
- Example : LNA, 900 MHz

techno CMOS 0,5 micron ; 2,7 V

NF = 1,9 dB

gain = 15,6 dB

IIP3 = –3,2 dBm

Power : 20 mW

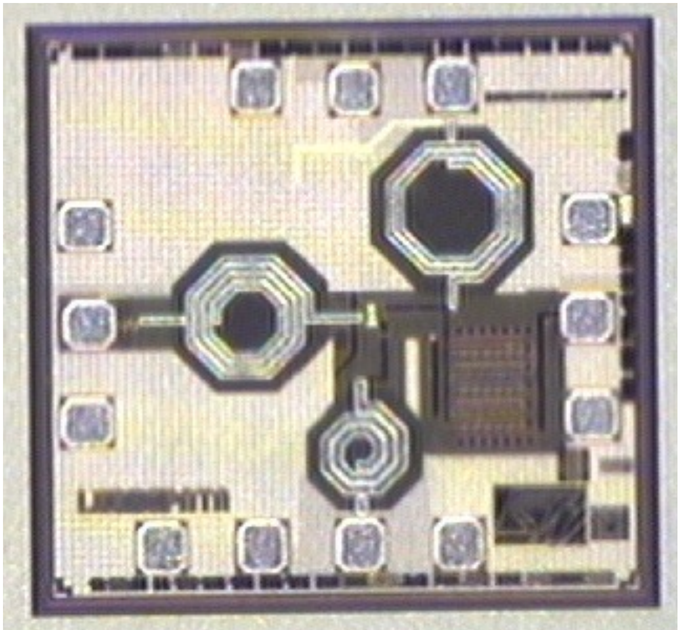
LNA results - summary

	LNA St Sub	LNA HR SUB
Freq. [GHz]	4	4
Gain [dB]	8	10.5
NF [dB]	2.2	2
ICP_{1dB} [dBm]	-13.5	-15
IIP3 [dBm]	-7.5	-10
Current [mA] V_{DD} = 1 V	6.6	6.6

Source ST Microelectronics

- With High resistivity, SOI substrate improves Inductors quality factor:
  - *$\Delta NF \sim 0,2$ dB*
  - *$\Delta G \sim 2,5$ dB ⇔ ~x2 output power*

Factor Of Merit Improvement



RF Mixer

0.01MHz to 4GHz Low Power Active Mixer
Application : Low Cost 900MHz Downconverting Mixer

Typical values:
At 900 MHz output
NF : 9,3 dB
IIP3 : + 9 dBm
Gain : 2,4 dB

V_{DD} : 2,7 to 5V

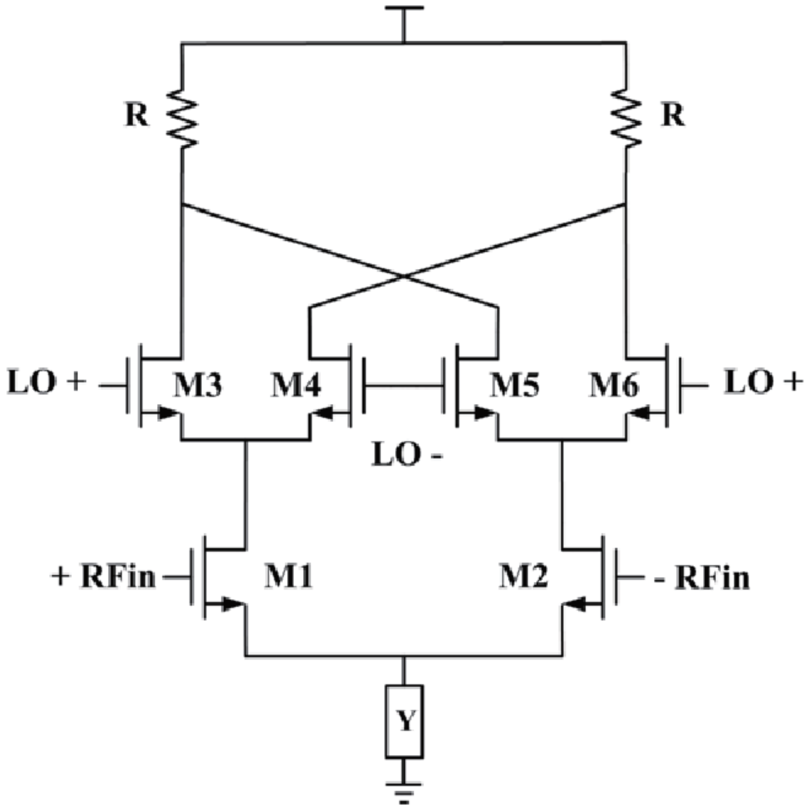


Figure 1. Conventional Gilbert cell schematic.

Conclusion

- **The Front-end RF more and more integrated and complex**
- **The techno BiCMOS and CMOS are used**
- **Enabling the move from 4G to 5G to 6G :**
  - evolution of carrier aggregation
  - more advanced modulation such as 256 QAM on the downlink and 64 QAM on the uplink.
  - wider range of frequency bands from 400MHz to 6GHz
  - backward compatibility to 4G/3G/2G operating modes
  - challenging RF blocks : LNA, Mixer, PA