LOW POWER RADIO COMMUNICATION SYSTEMS, NEW TRENDS AND CHALLENGES

2016 Summer school of Information Engineering – Technologies for IoT | Dominique Morche

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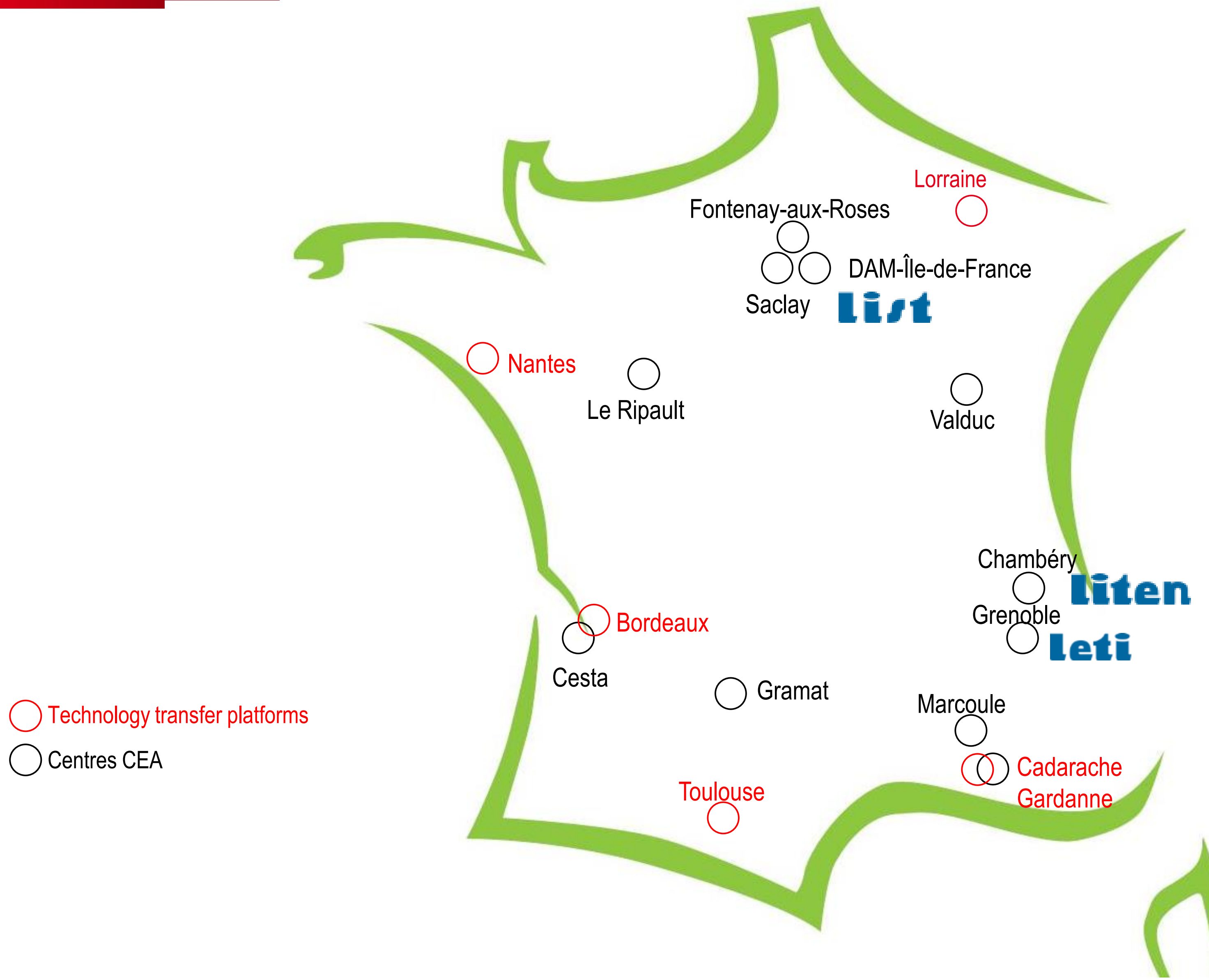
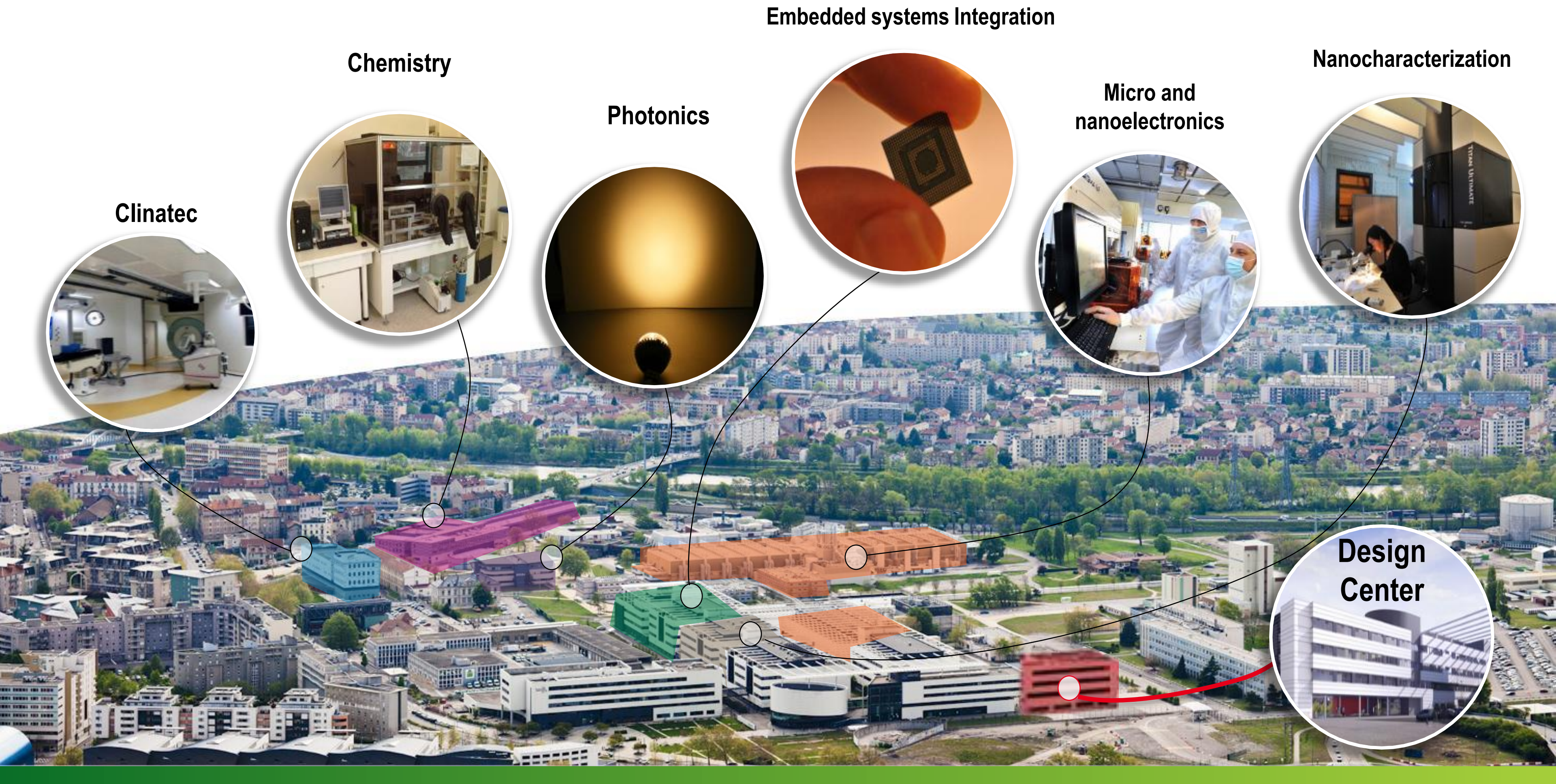
CEA LOCATION IN FRANCE

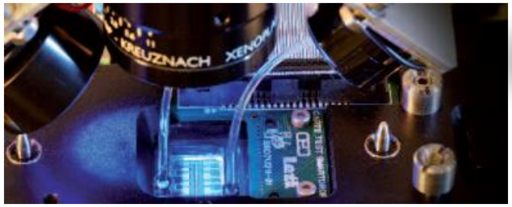


OUR RESEARCH PLATFORMS

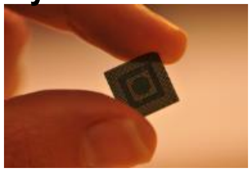


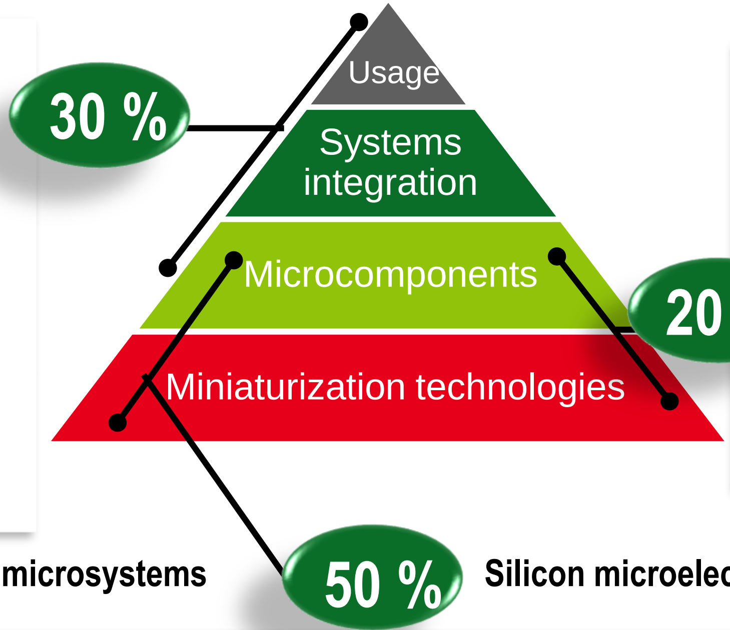
LETI ACTIVITY FIELDS

Systems for biology & healthcare



Systems for communication

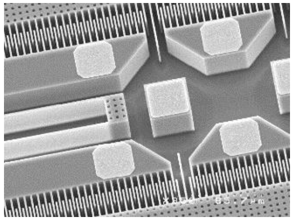


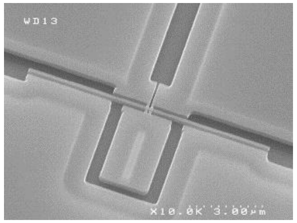


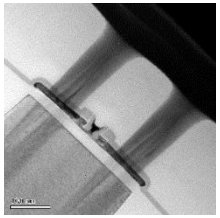
Optoelectronics components

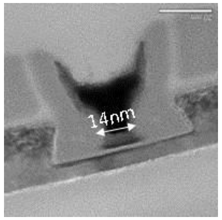
Silicon microsystems

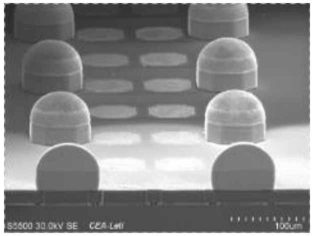
Silicon microelectronics

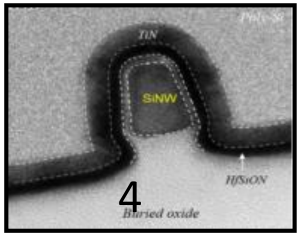




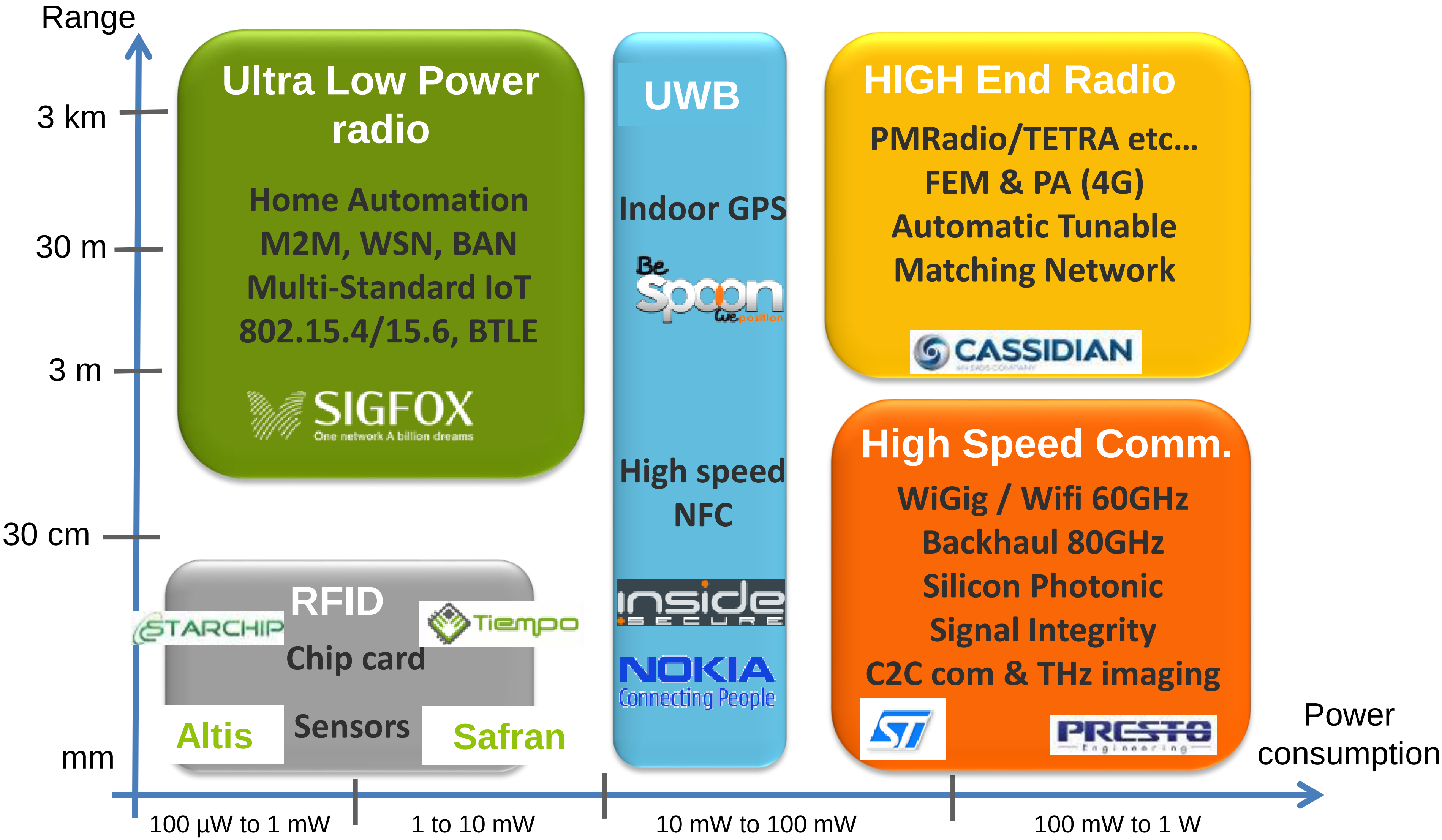








RF DESIGN - OVERVIEW



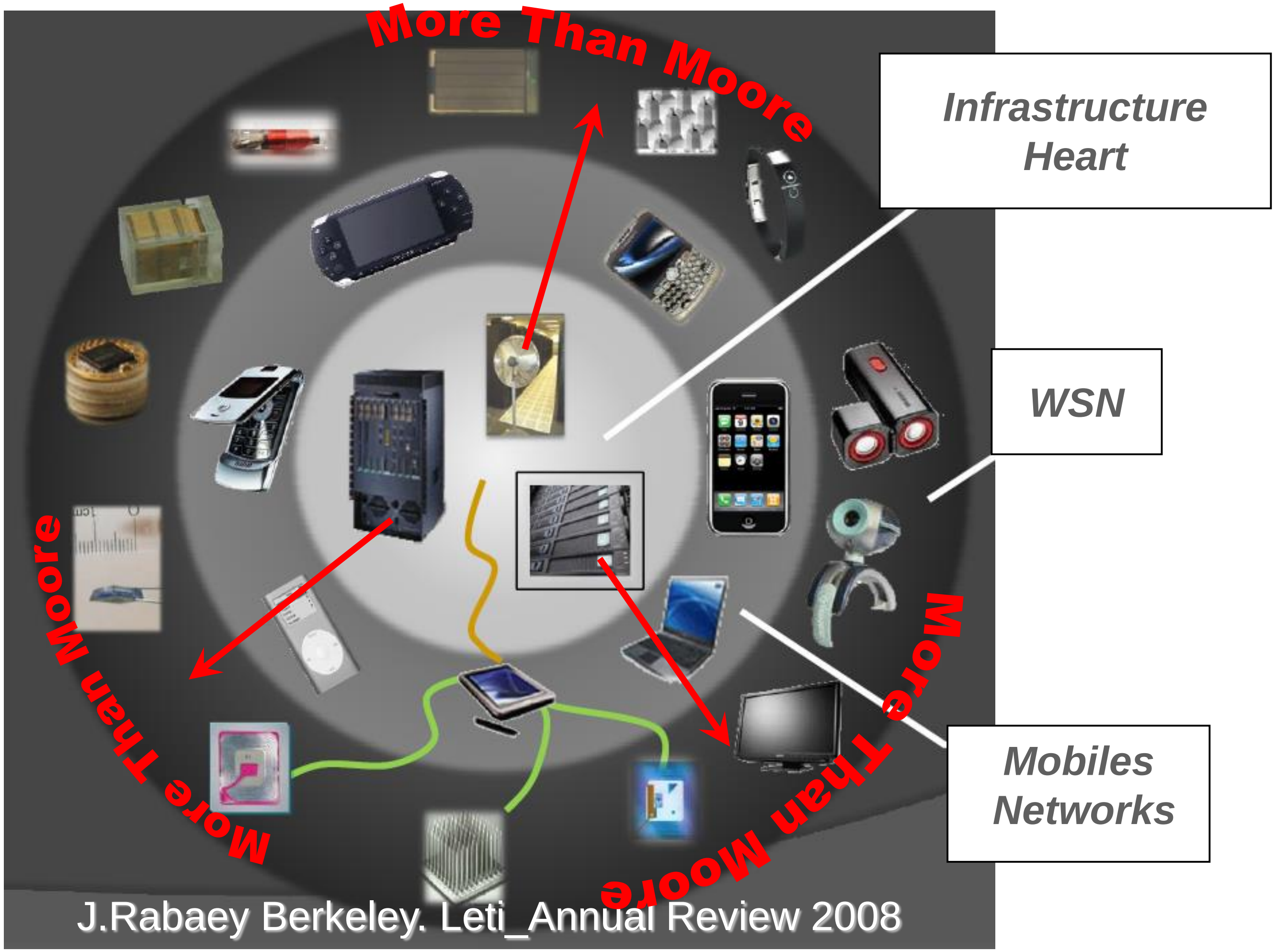
PRESENTATION OUTLINE

1. Introduction and Pre-requisites
2. Adaptive Radio
3. Wake-Up Radio
4. Ultra-Narrow-Band Approach
5. Conclusions

PRESENTATION OUTLINE

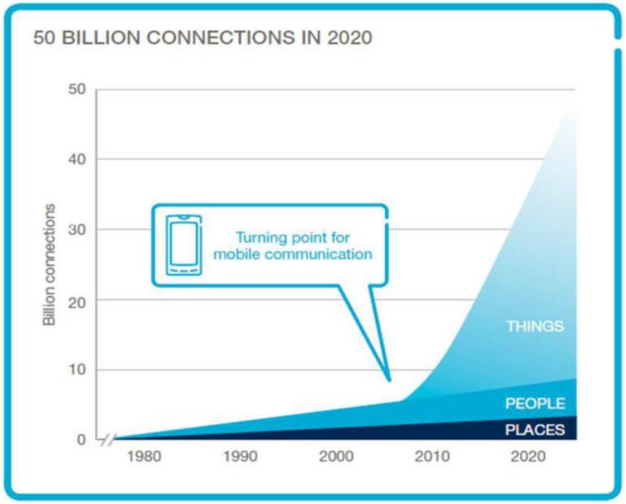
1. **Introduction and Prerequisites**
   - Market & Forecast
   - Buzz World or Reality
   - Radio Issues
2. **Adaptive Radio**
3. **Wake-Up Radio**
4. **Ultra-Narrow-Band Approach**
5. **Conclusions**

GLOBAL VISION



MARKET EVOLUTION

- **EveryBody agree**



50 Billion Connections in 2020 – Ericsson (from page 18 of 2010 annual report)

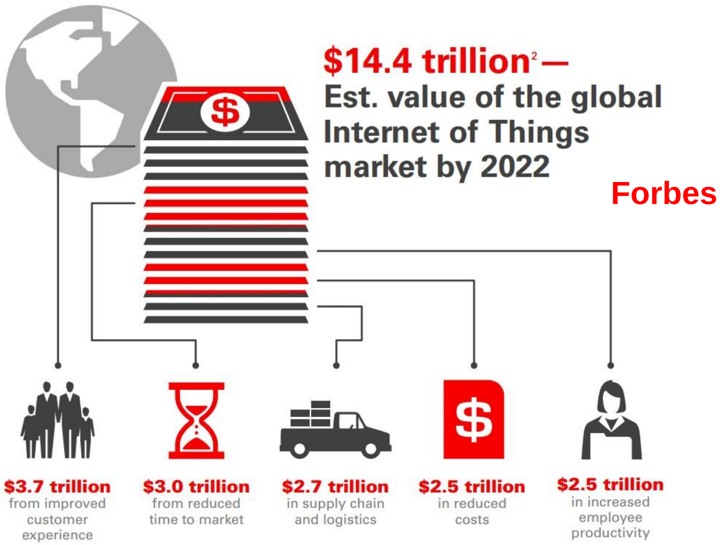
World population :	6,3 Billion	6,8 Billion	7,2 Billion	7,6 Billion
Connected devices :	500 Million	12,5 Billion	25 Billion	50 Billion
Connected devices Per Person	0,08	1,84	3,47	6,58
	2003	2010	2015	2020

Source: Cisco IBSG, 2011

More connected devices than people

The global business impact of the Connected Life can be split into two broad categories: 'new revenue opportunities' and 'cost reduction and service improvements'[6]:

- In 2020, revenues from the sale of connected devices and services, and revenues from related services, such as pay-as-you-drive car insurance, will be worth US$2.5 trillion, US$1.2 trillion of which could be addressed by mobile operators and the remainder by the broader Connected Life ecosystem.
- Cost reductions and service improvements relate to less direct, but tangible, benefits to organisations, governments and consumers through the evolution of the Connected Life. In 2020, this could be worth approximately US$2 trillion: US$1 trillion from cost reductions, such as smart meters removing the need for manual meter readings; and US$1 trillion from service improvements, such as clinical remote monitoring for patients with chronic illnesses.



IT'S AN OLD STORY

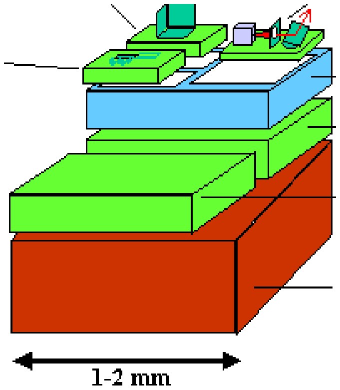
- **Home Automation Market Booming was expected in 80s, 90s…**

  https://youtu.be/9V_0xDUg0h0

  https://youtu.be/-T9VD8mIegY

- **Communicating Objects**

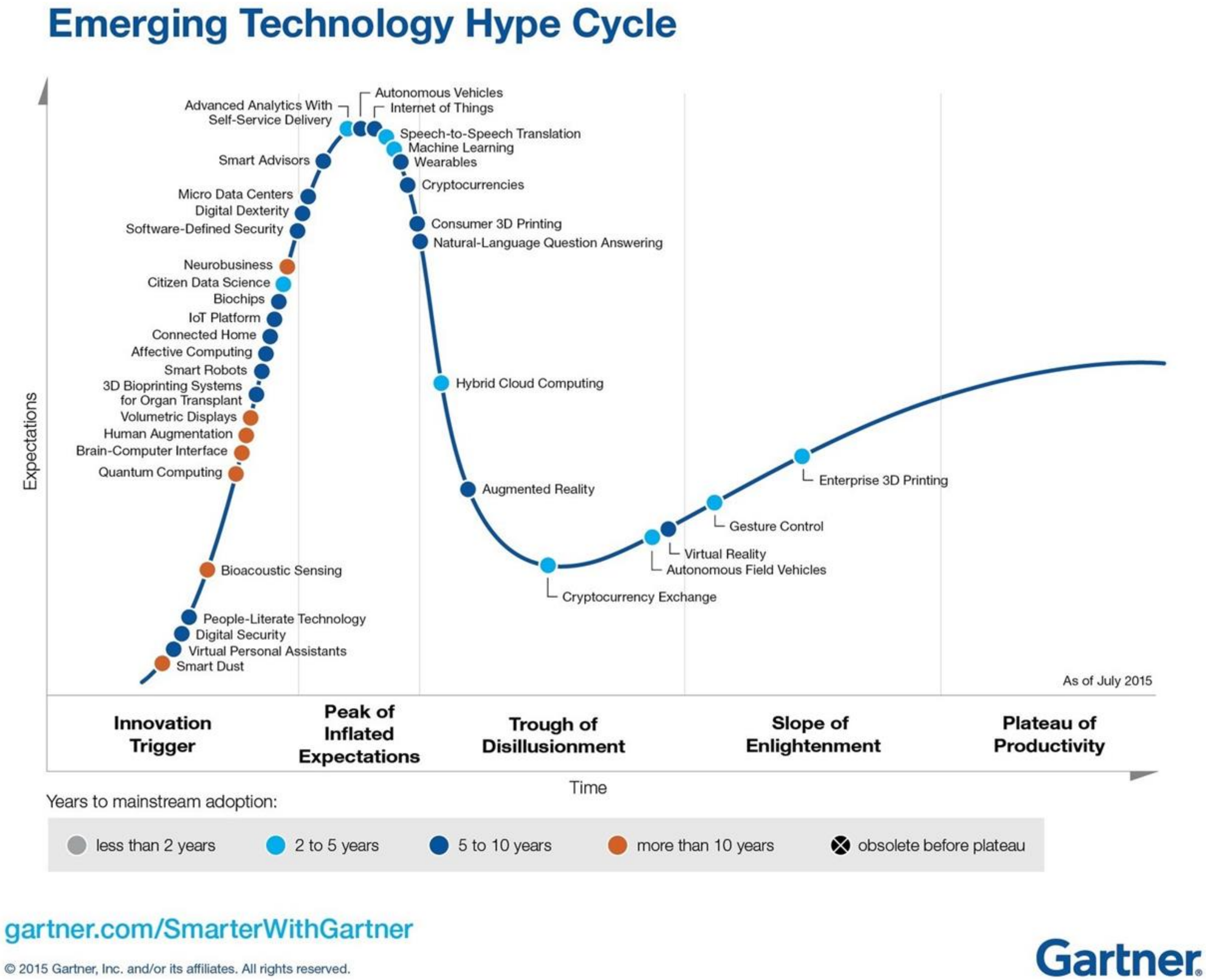
"Autonomous sensing and communication in a cubic millimeter"



Smart Dust

By Kris.Pister (Berkeley)
Started in 1997

HYPE CYCLE


Emerging Technology Hype Cycle
Expectations
Advanced Analytics With Self-Service Delivery
Autonomous Vehicles
Internet of Things
Speech-to-Speech Translation
Machine Learning
Wearables
Smart Advisors
Cryptocurrencies
Micro Data Centers
Digital Dexterity
Software-Defined Security
Consumer 3D Printing
Natural-Language Question Answering
Neurobusiness
Citizen Data Science
Biochips
IoT Platform
Connected Home
Affective Computing
Smart Robots
3D Bioprinting Systems for Organ Transplant
Hybrid Cloud Computing
Volumetric Displays
Human Augmentation
Brain-Computer Interface
Quantum Computing
Enterprise 3D Printing
Augmented Reality
Gesture Control
Virtual Reality
Autonomous Field Vehicles
Bioacoustic Sensing
Cryptocurrency Exchange
People-Literate Technology
Digital Security
Virtual Personal Assistants
Smart Dust
As of July 2015
Innovation Trigger
Peak of Inflated Expectations
Trough of Disillusionment
Slope of Enlightenment
Plateau of Productivity
Time
Years to mainstream adoption:
less than 2 years
2 to 5 years
5 to 10 years
more than 10 years
obsolete before plateau
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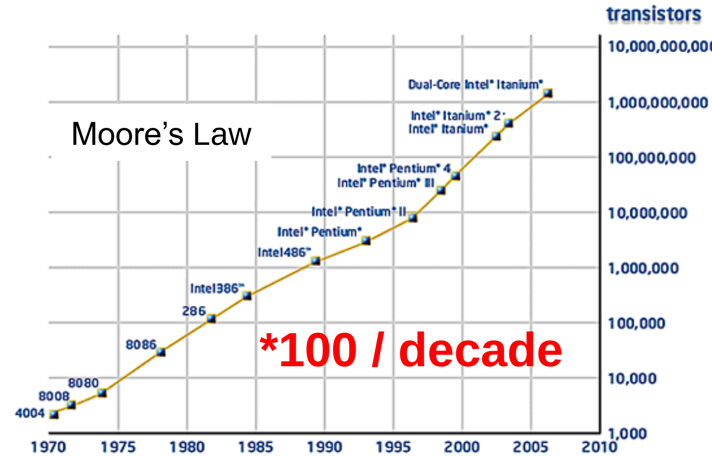
POTENTIAL REASON FOR A SUCCESS



Convergence

Micro & nano Technologies

+

Data Base Information Processing

+

Internet & network technologies

Cost

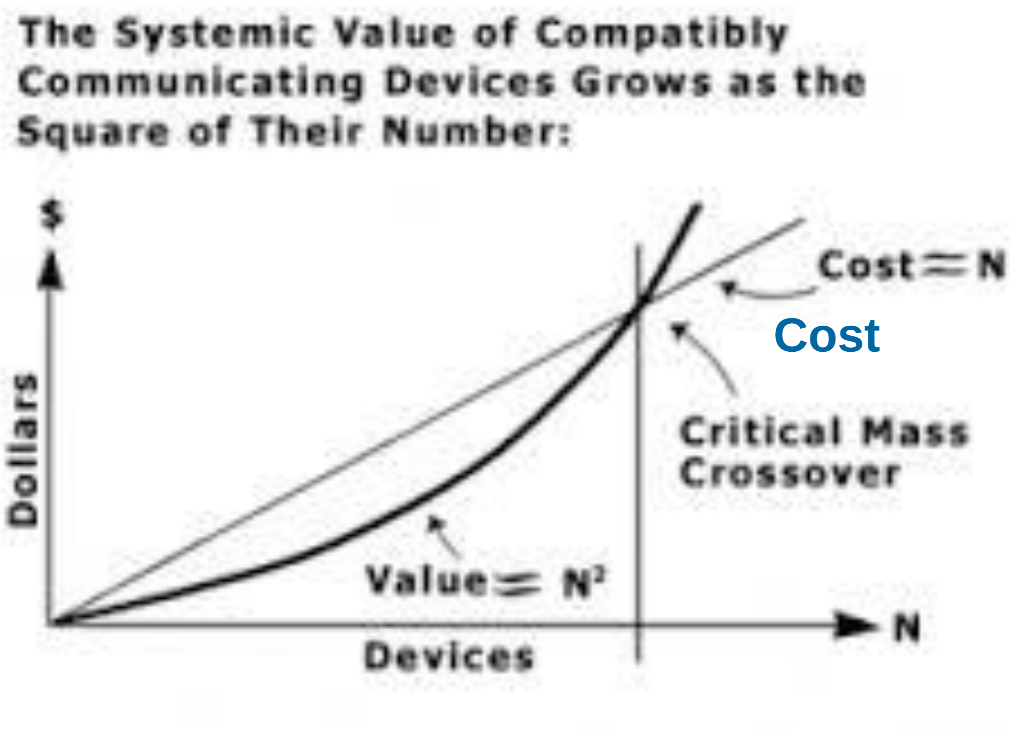
(1MT cost was 6c€ in 2000 and 0,06c€ in 2010)

Power

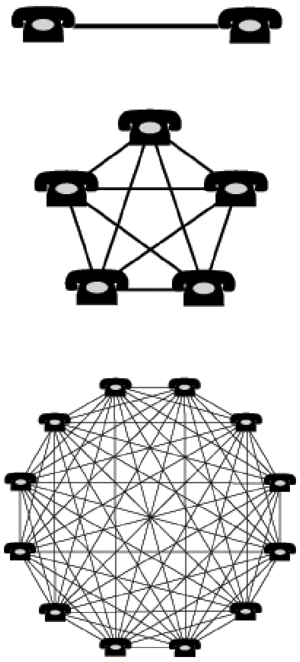
(MacBook Air with 1992 energy efficiency would have an autonomy of 1.5s)

NETWORK COST AND VALUE

- MetCalfe Law



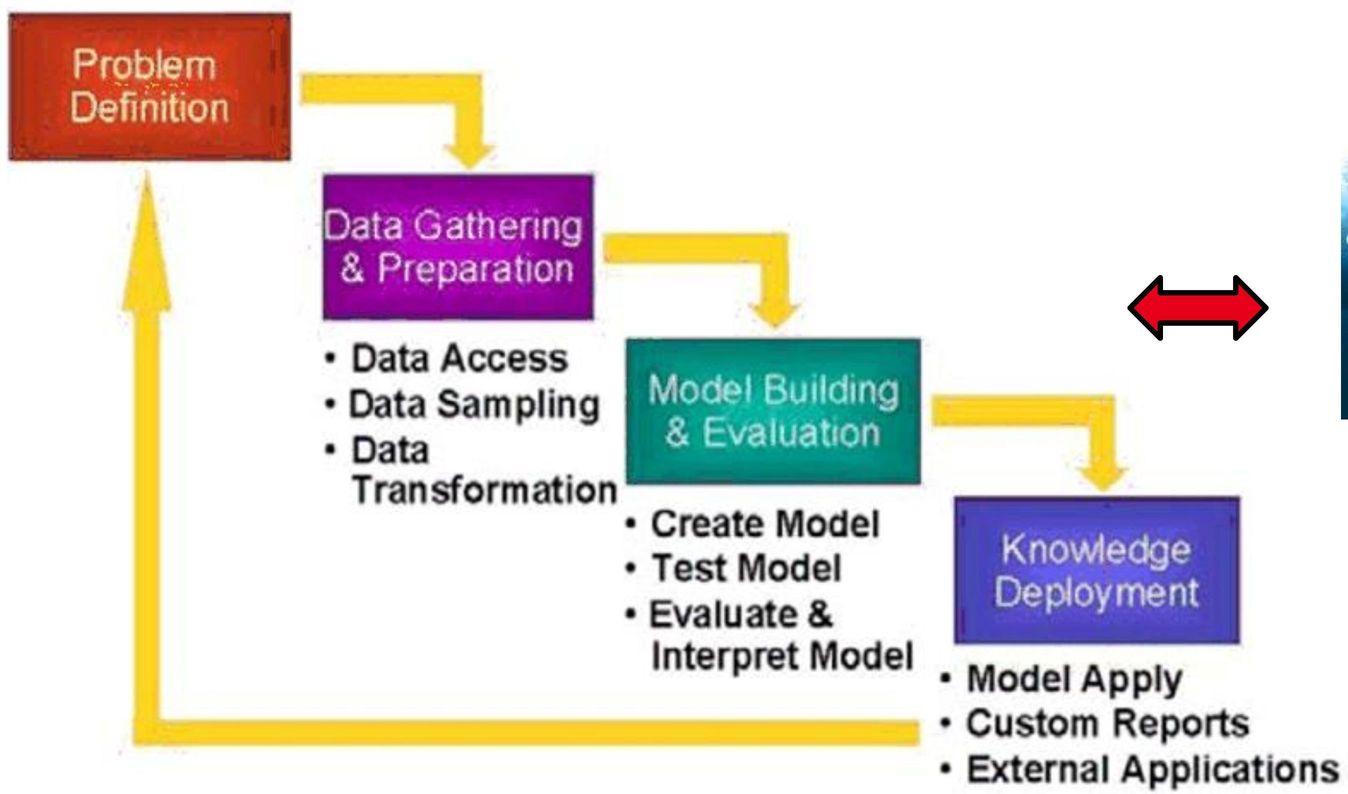
foundational law for social networking platforms



An Ocean of Data

BIG DATA ANALYTICS

- Find the right information thanks to statistics

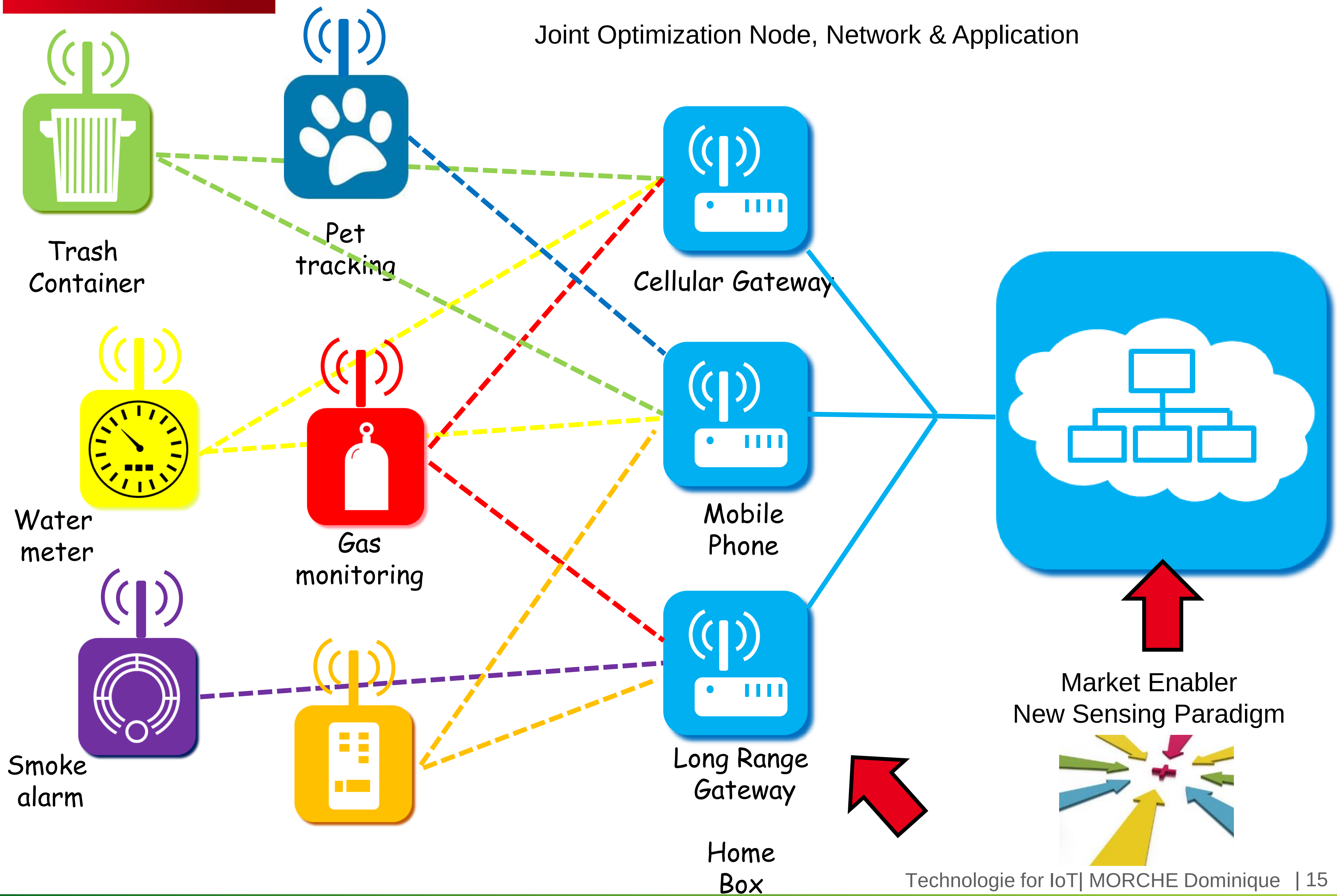


- Can compete with specialists

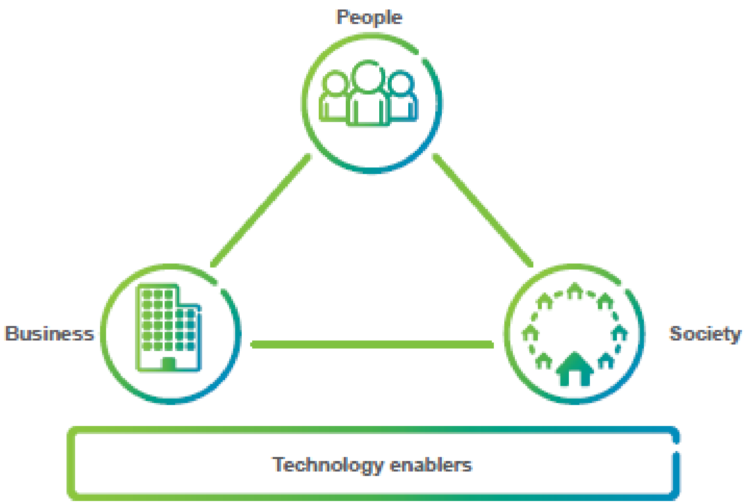
- Data Markets

IOT CONNECTIVITY

Joint Optimization Node, Network & Application



IOT ENABLERS AND OPPORTUNITIES



New Services

- Health Monitoring
- Home Automation
- SHM

New Challenges

- GreenHouse Gas
- Renewable Energy
- Population Density
- Pollution

New Business Models

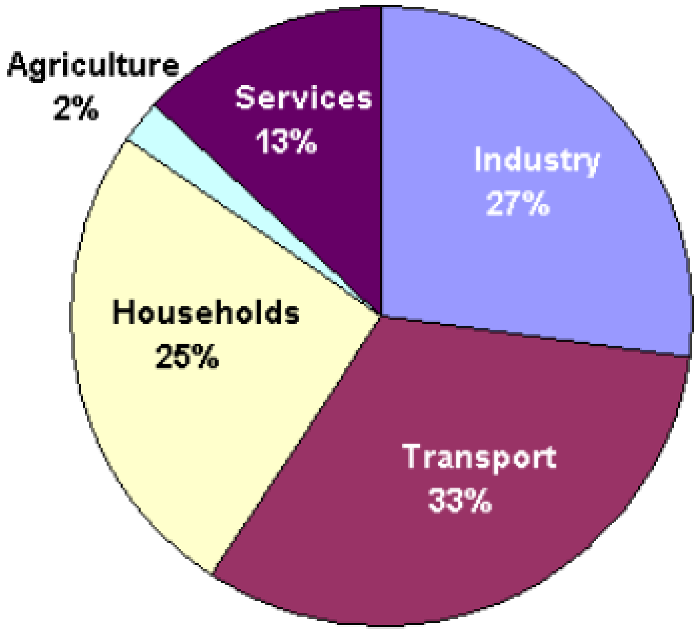
- Data Monetization
- Services vs HW
- Usage based pricing

you can only optimize what you can measure

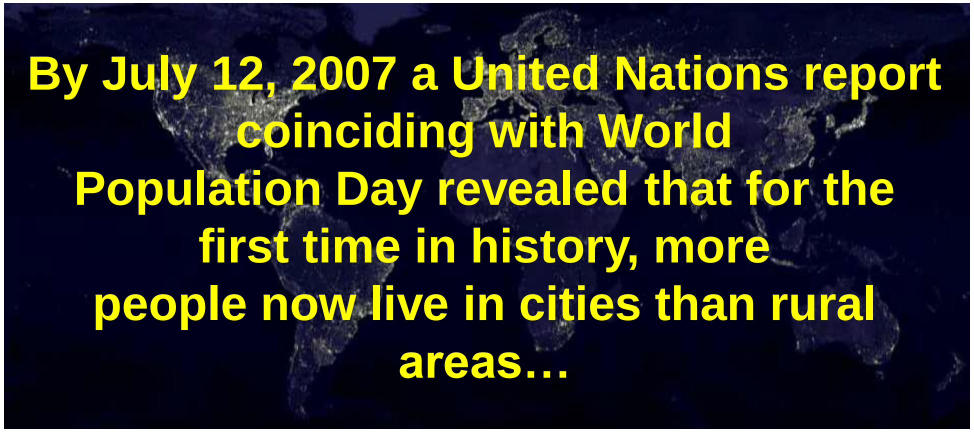
ENERGY CONSUMPTION IN EUROPE

Society

Smart Cities have been recently pointed by experts as an emerging market with enormous potential, which is expected to drive the digital economy forward…



EU-27 Total Final Energy Consumption (2008) Total = 1168.63 Mtoe



Transport and households consume more than half of the total energy in the EU, while a quarter of energy is consumed by industry.

"The 19th century was a century of empires, the 20th century was a century of nation states, the 21st century will be a century of cities"
Wellington E. Webb, former mayor of Denver

INDUSTRIAL MONITORING (CONTROL) : INDOOR

- **Sensed Area :**

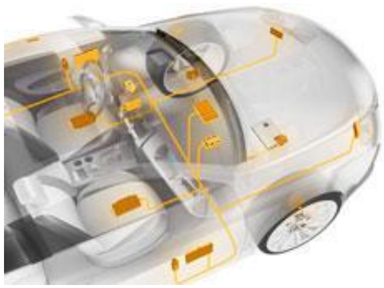
Industries, Machines, Warehouse, GreenHouse,

- **Sensed informations :**

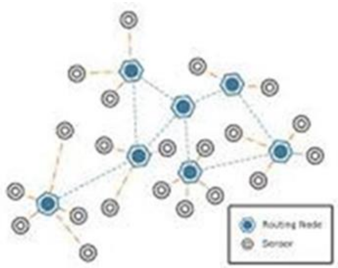
Power, Pression, Humidity, Temperature, People, Goods localisation, Machine State, …

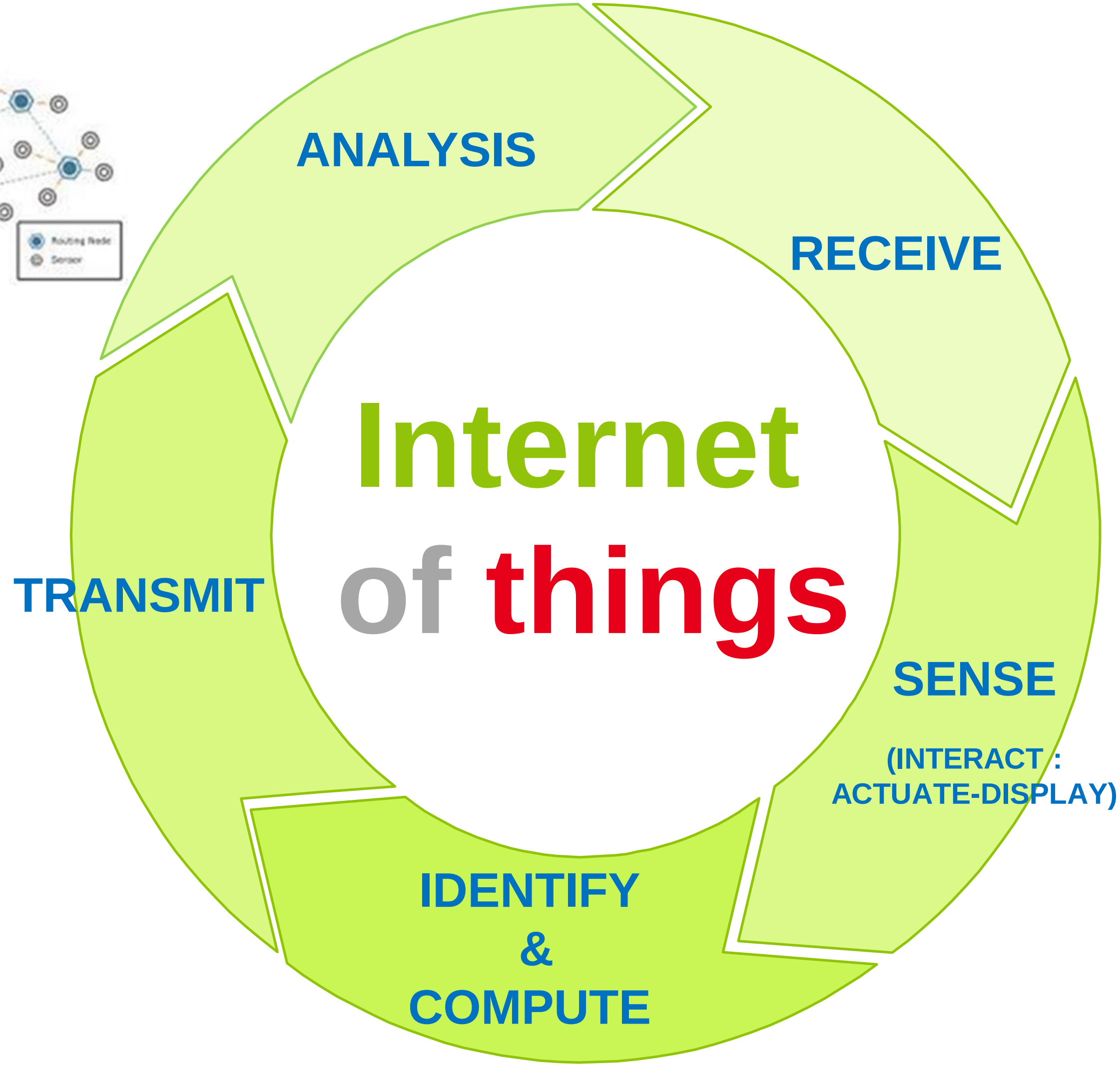
- **Targeted Applications**

Production monitoring, Maintenance Planning, temperature control, Security, Water quality




WHAT IS AN IOT NODE



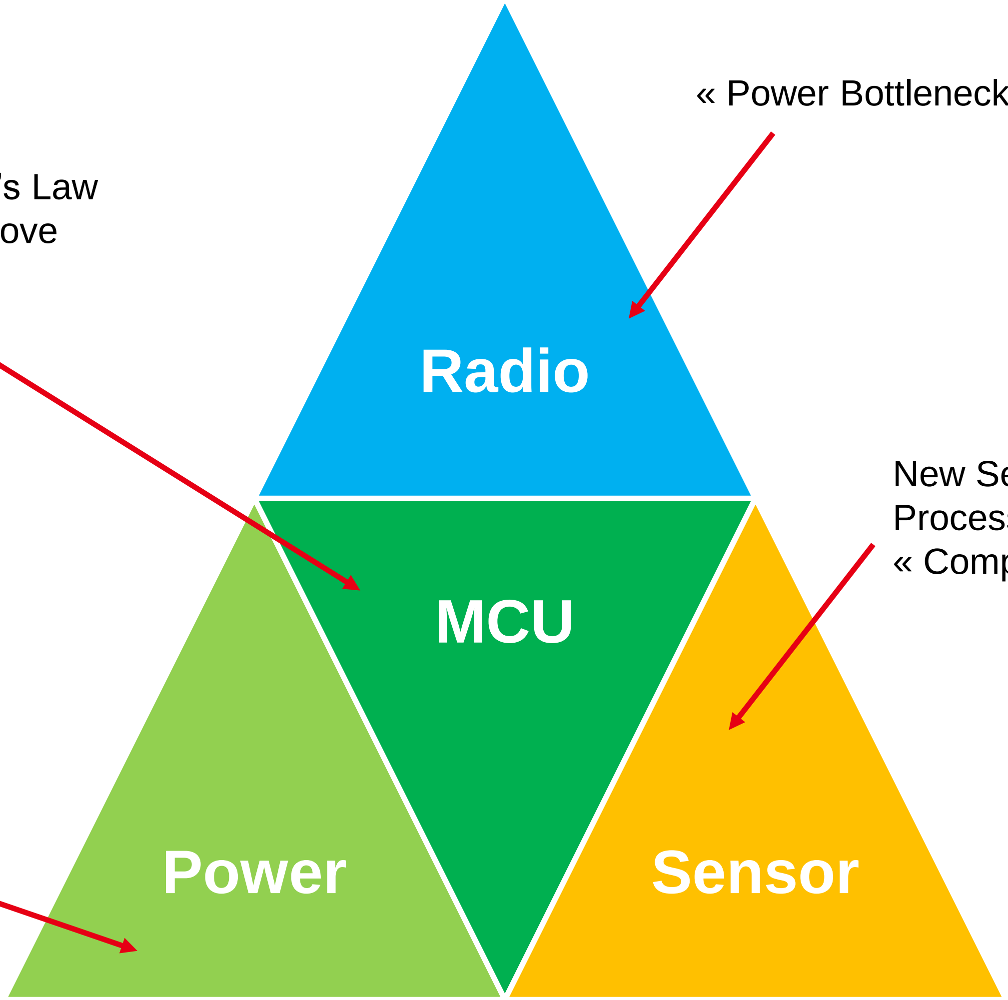


"**network** of physical objects that contain embedded technology to communicate and sense or interact with their internal states or the external environment"

IOT NODE ARCHITECTURE

« Power Bottleneck »

Take benefit of Moore's Law
- Performances improve
- Power decrease

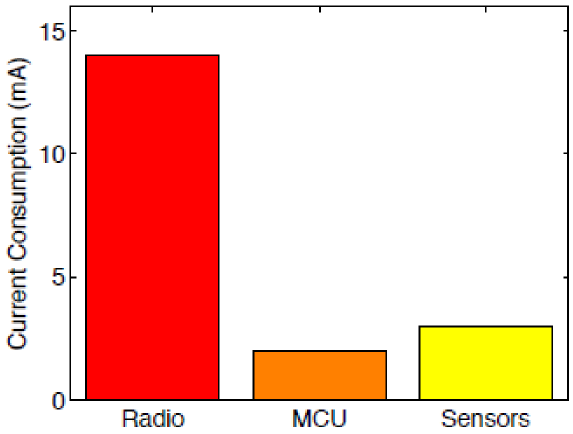


New Sensing &
Processing approach
« Compress Sensing »

No moore's Law

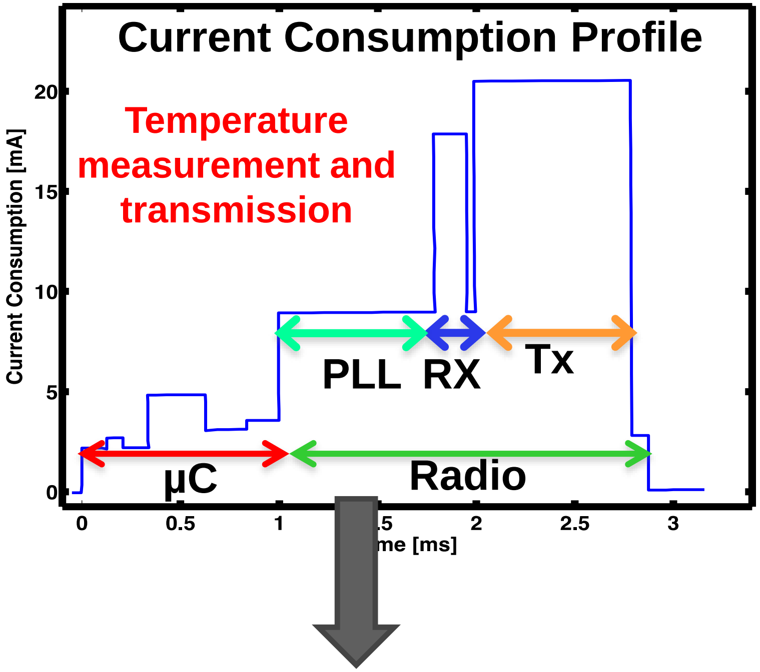
POWER ISSUE IN IOT

- Radio transceiver is often the most energy hungry block in a WSN node

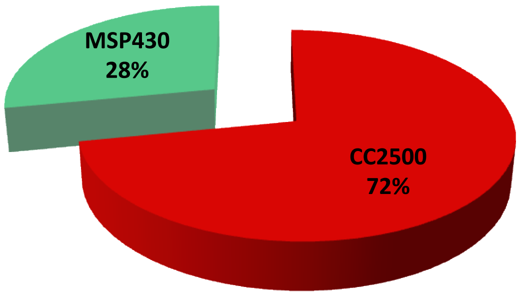


Malik et al. : MAC Essentials for Wireless Sensor Networks

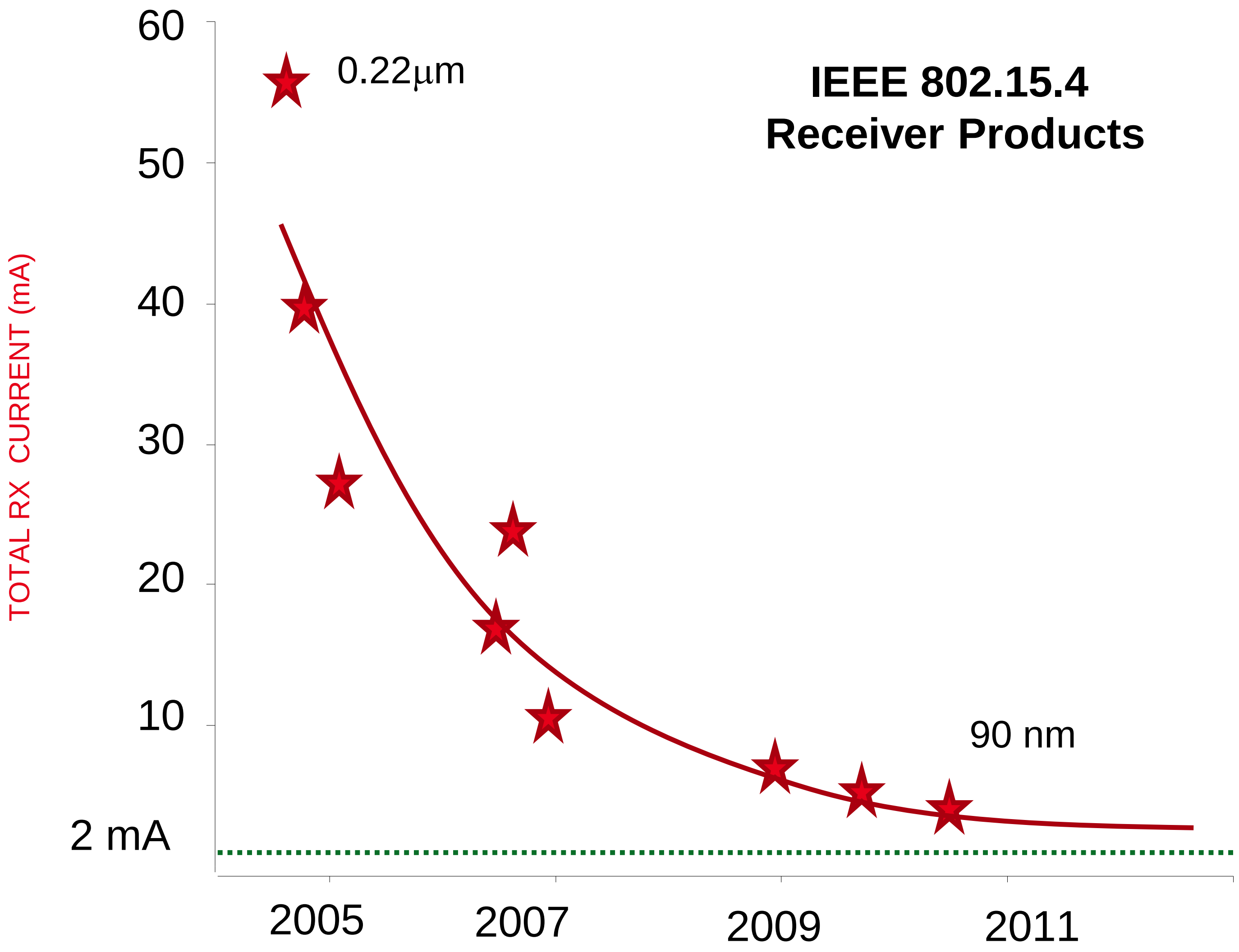
- Use case: eZ430-RF2500 sensor node



Energy Consumption of the MSP430 and CC2500



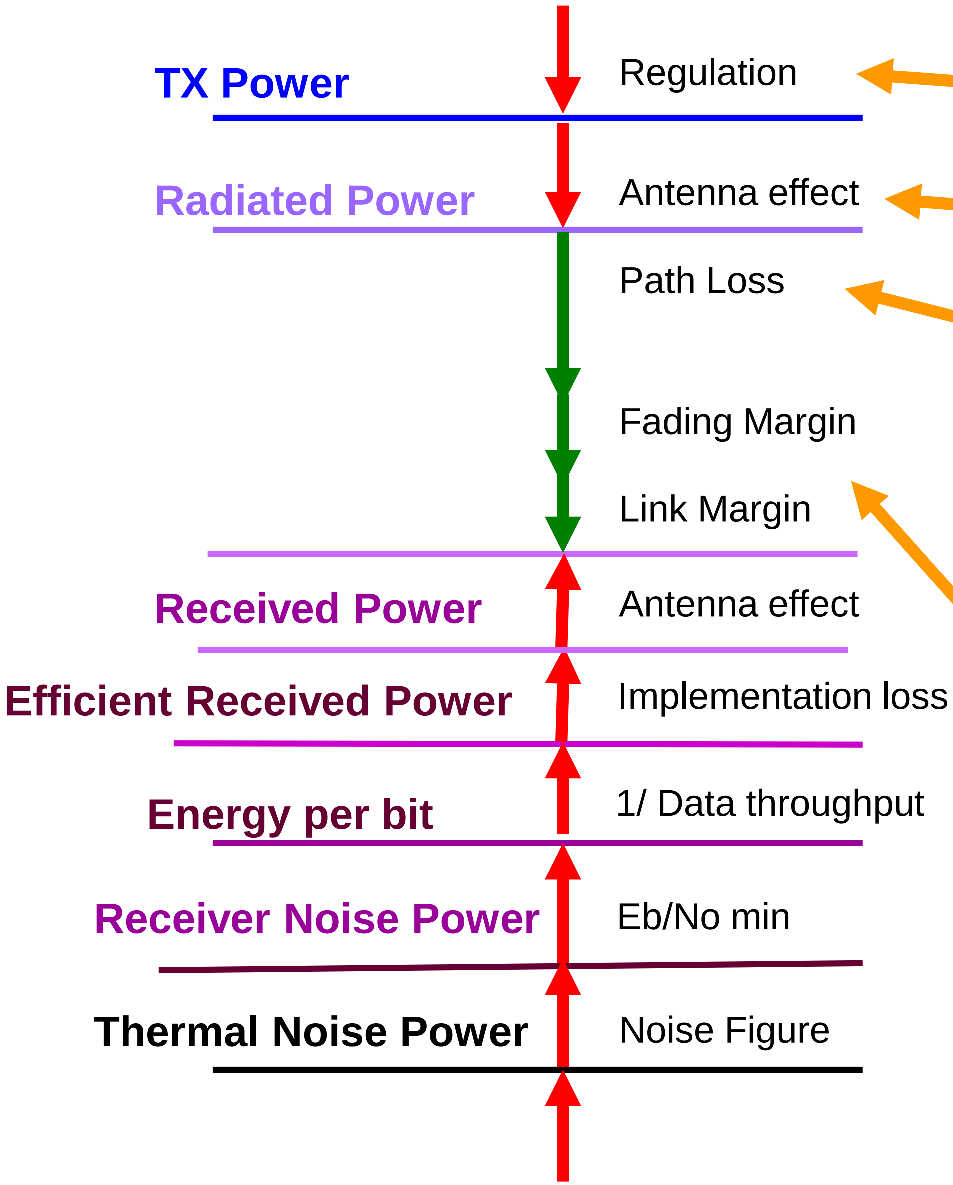
POWER CONSUMPTION EVOLUTION



NEW SOLUTIONS SHOULD BE FOUND

- **Analysis of current situation**
  - Power correlated to the dynamic range
  - Justifiy the low signal limit : sensitivity
    - Budget Link
  - Justifiy the high signal limit
    - Near-Far Effect

BUGDET LINK ANALYSIS (1/4)



Regulation : CEPT, FCC

Standard : ETSI, IEEE,,

Antenna Gain, Antenna efficiency, body loss

Power scaling constant

$$PL_{dB}(d) = n \cdot 10\log_{10}(d) + c$$

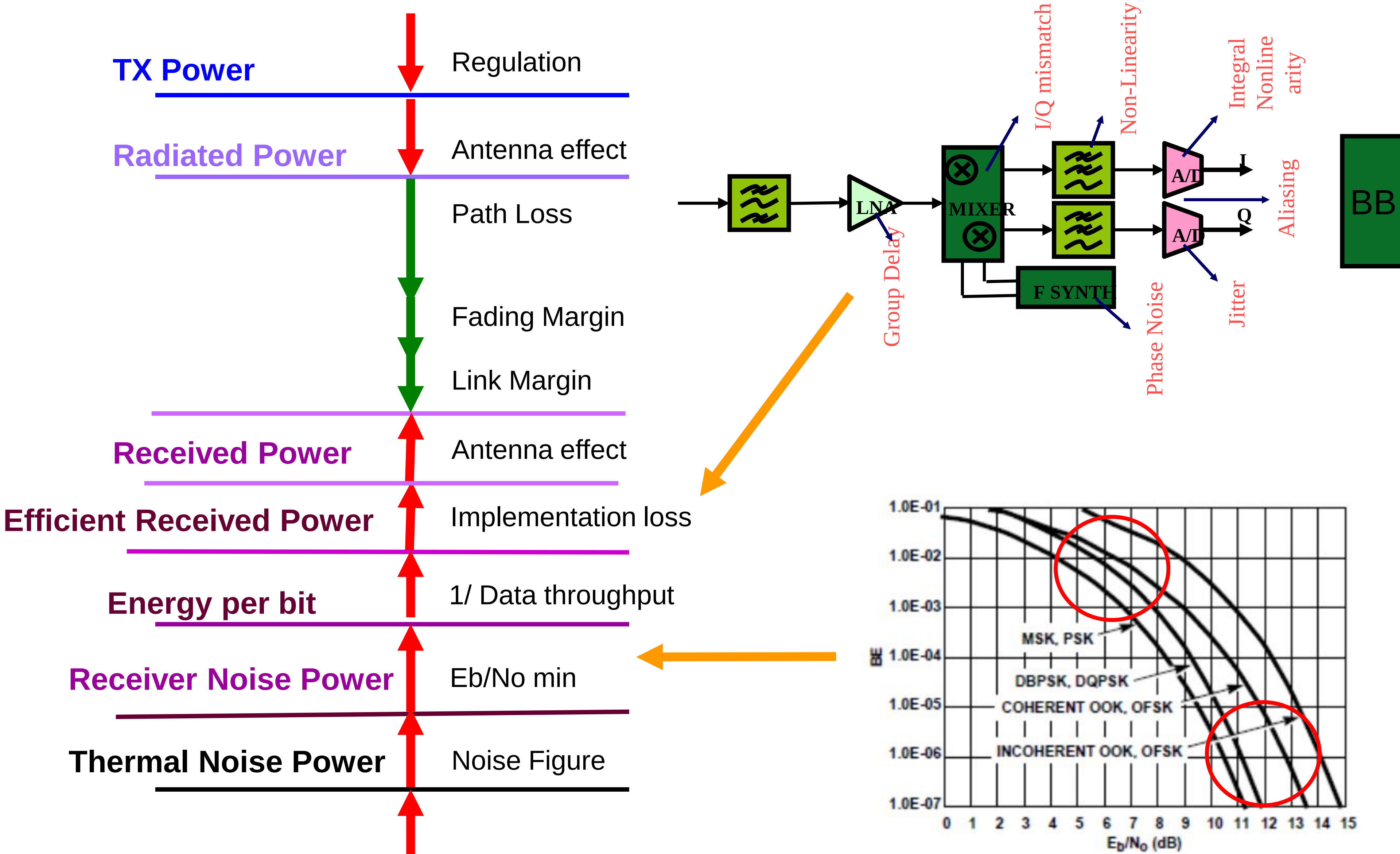
Path loss exponent

Time Availability (%)	Fade Margin (dB)
90	8
99	18
99.9	28
99.99	38
99.999	48

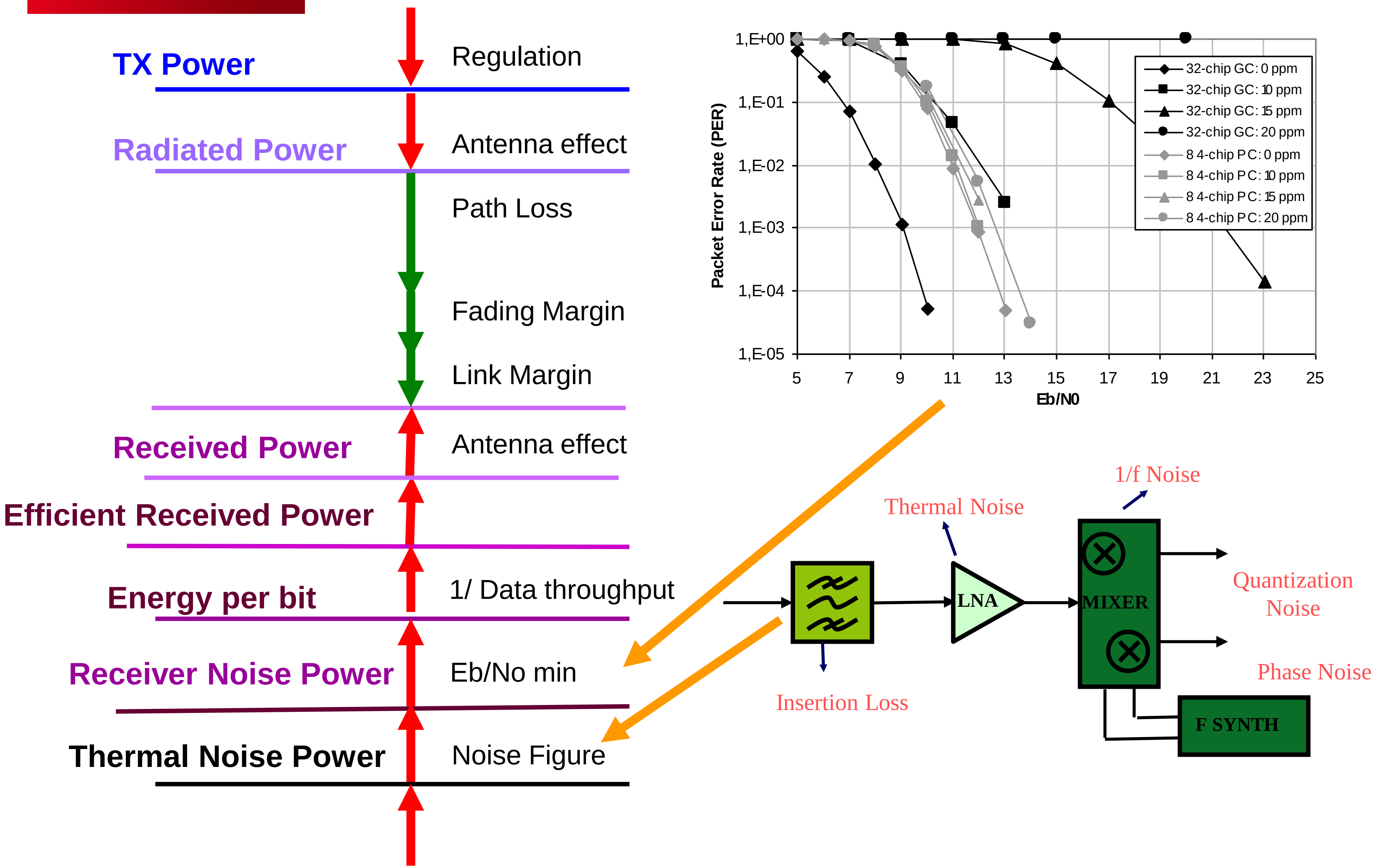
Table 3: Rayleigh Fading Model

$$PL_{dB}(d,f) = \underbrace{20\cdot\log_{10}(4\pi) + 20\cdot\log_{10}}_{22}\left(\frac{df}{c}\right)$$

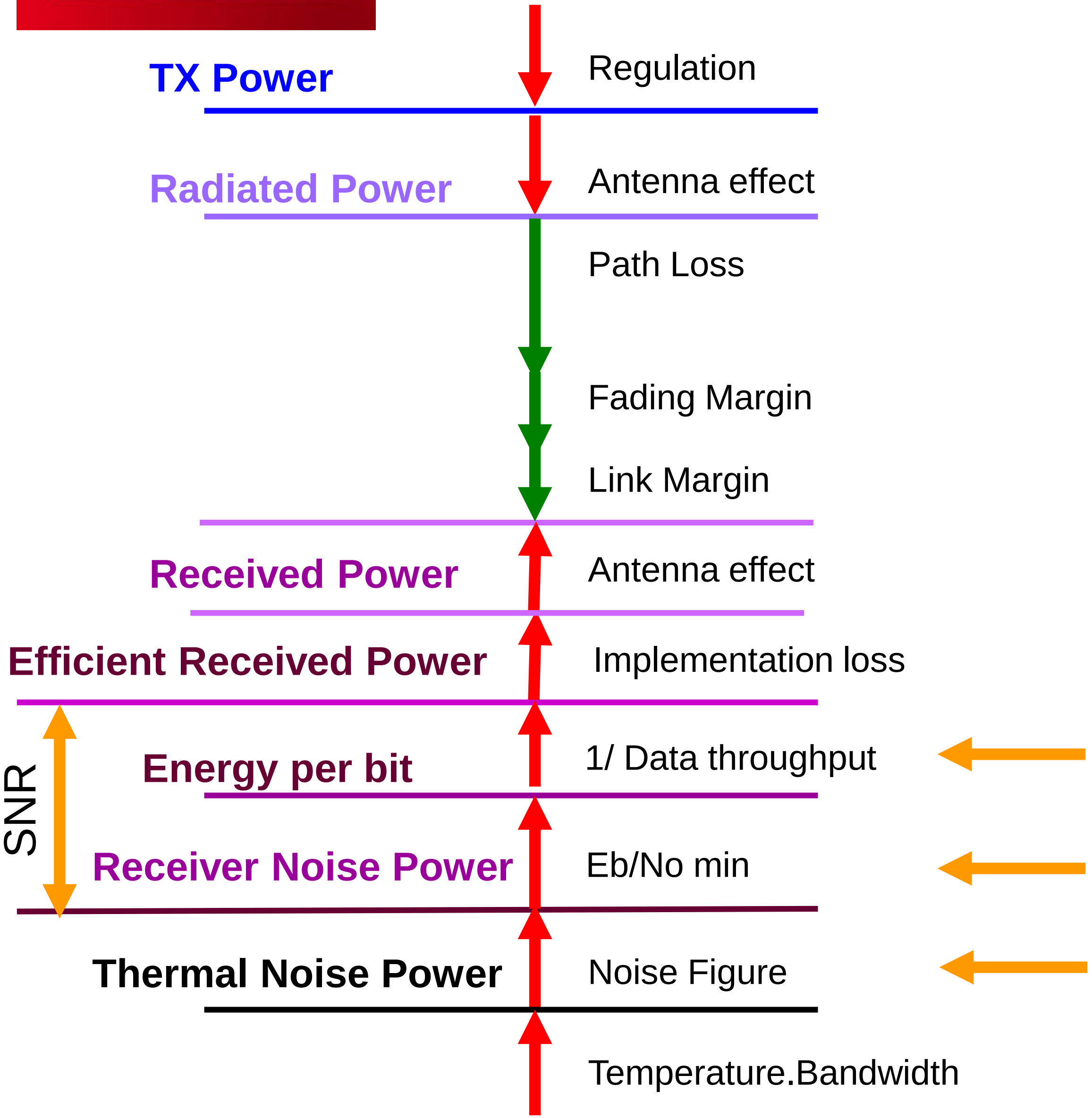
BUGDET LINK ANALYSIS (2/4)



BUGDET LINK ANALYSIS (3/4)



BUGDET LINK ANALYSIS (4/4)



SNR=(Eb/No)*(R/B)

where

Eb = Energy required per bit of information

No = thermal noise in 1Hz bandwidth

R= system data rate

B = System bandwidth

N=kTB

where

N = noise power (dBm)

K = boltzman's constant (1.38 *10-23 j/K)

T = system temperature, usually (assumed to be 290 K)

B = Channel Bandwidth

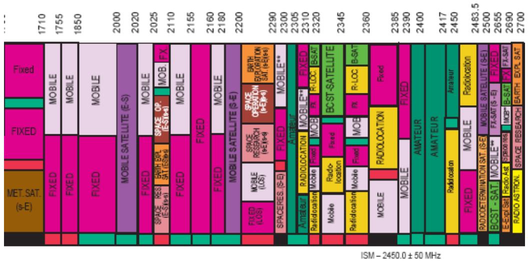
BUGDET LINK COMPARISON

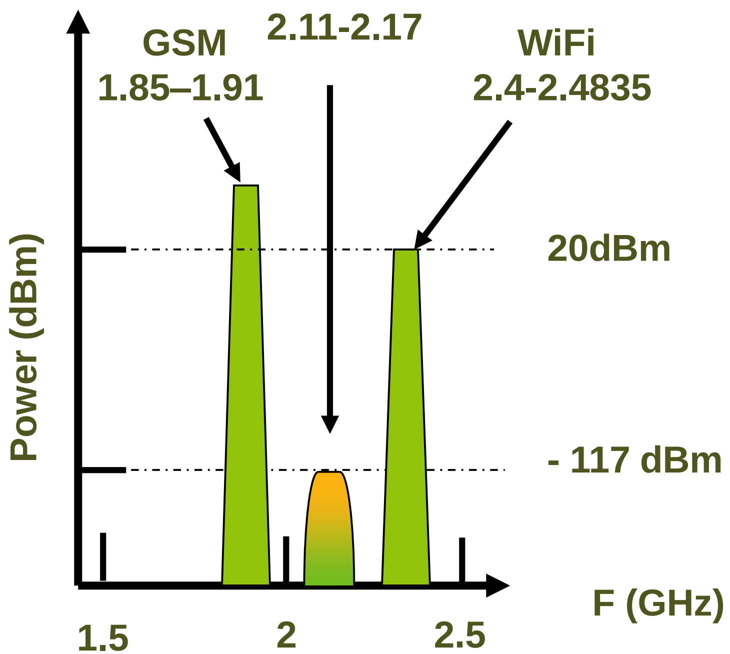
Power level	Factor	Cellullar	M2M
TX Power	Regulation	+++	---
Radiated Power	Antenna effect	--	++
	Path Loss	+++	--
	Fading Margin		
	Link Margin		
Received Power	Antenna effect	-	--
Efficient Received Power	Implementation loss	-	++
Energy per bit	1/ Data throughput	+	++
Receiver Noise Power	Eb/No min	--	++
Thermal Noise Power	Noise Figure	-	+
	Temperature.Bandwidth		

SNR

WIRELESS SPECTRUM CONSTRAINTS

- **Independent Wireless System Cohabitation**
  - First Issue : Blocking Signals

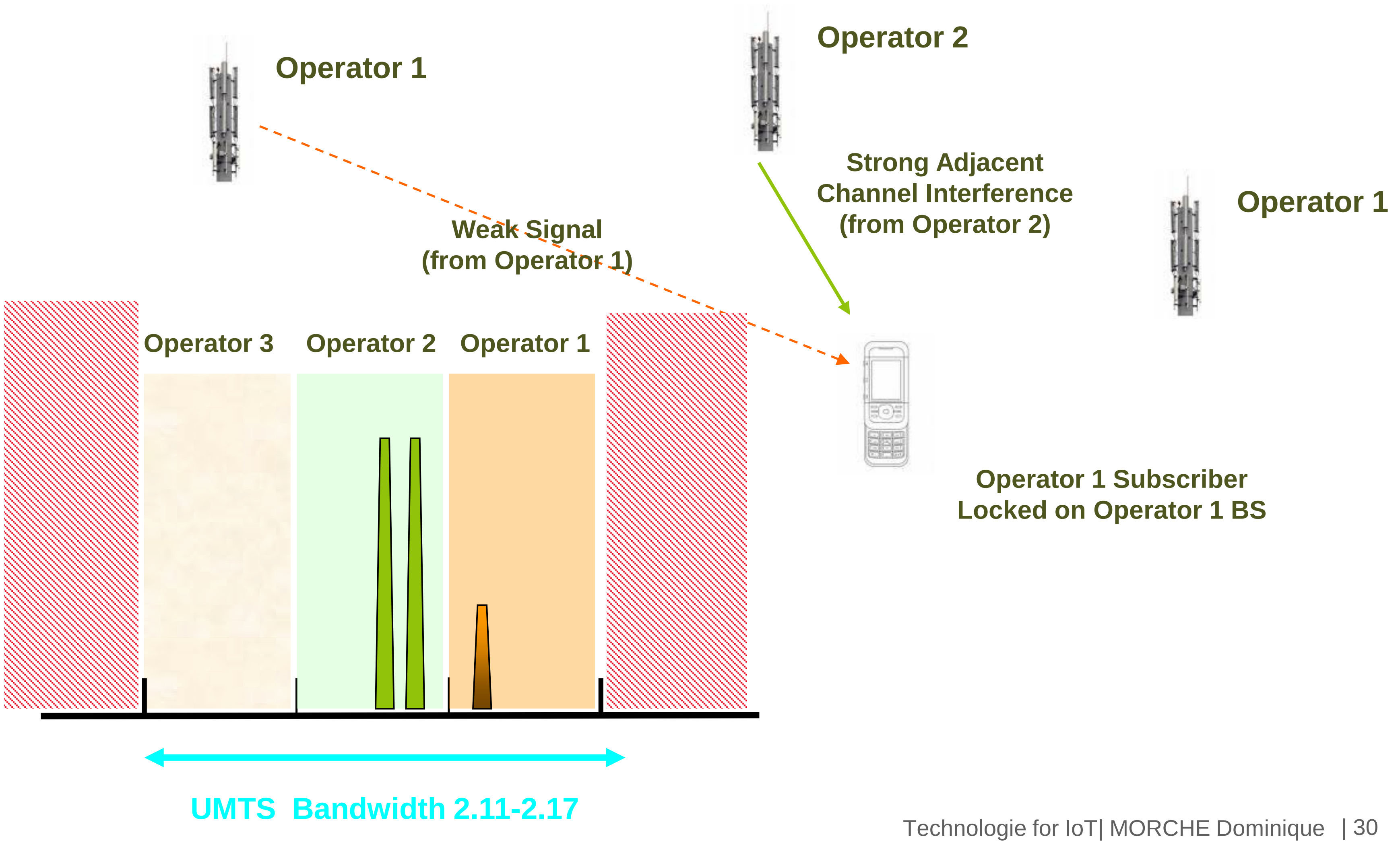




GSM UMTS Wi Fi

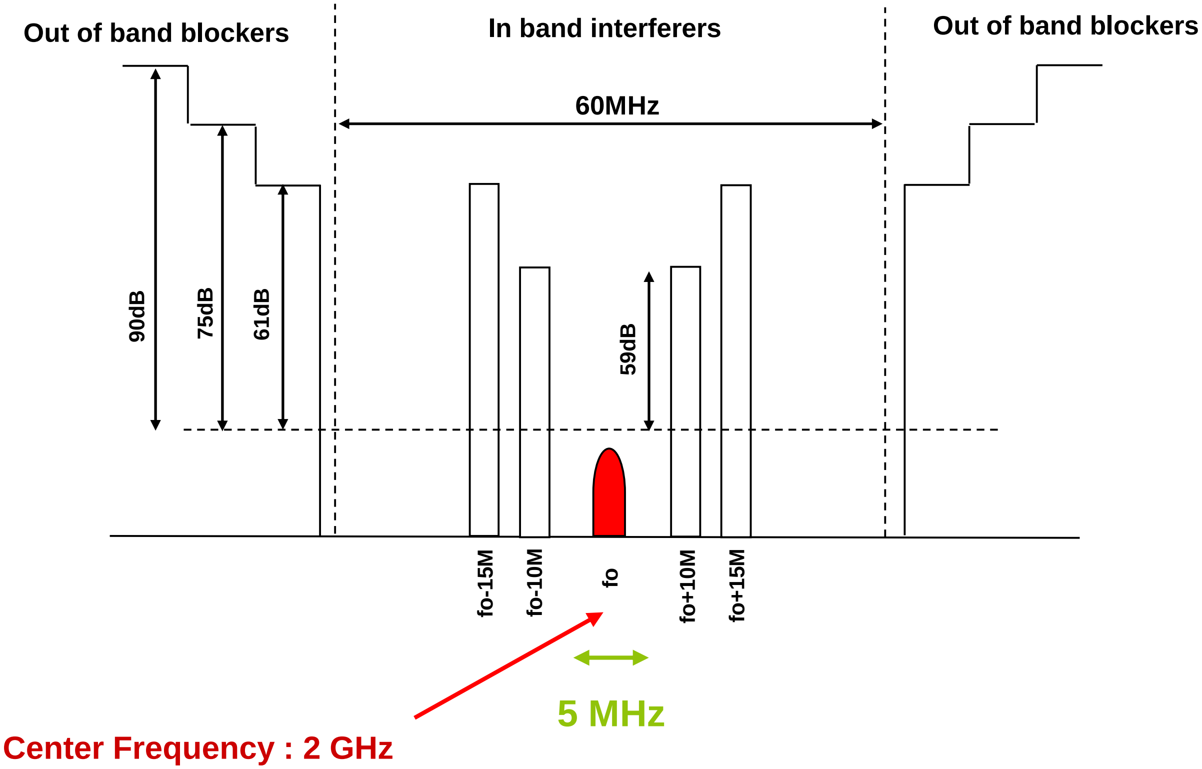
WIRELESS SPECTRUM CONSTRAINTS

- **Independent Operator Cohabitation**



Final Receiver Constraints

- Filtering Mask



SUM-UP

- **Radio Power consumption is often dominating the IoT node power and can limit the spreading of IoT**

- **Radio power consumption is not scaling**
  - To maintain a good sensitivity
  - To be robust againt parasitics RF Signals : does not improve

- **Some solutions should be found**

PRESENTATION OUTLINE

1. **Introduction and Prerequisites**

2. **Adaptive Radio**
   - Motivation
   - Basic Approach
   - Limitations

3. **Wake-Up Radio**

4. **Ultra-Narrow-Band Approach**

5. **Conclusions**

- Smart Radio
- Self Healing Radio
- Sense & React
- Zero Margin Radio

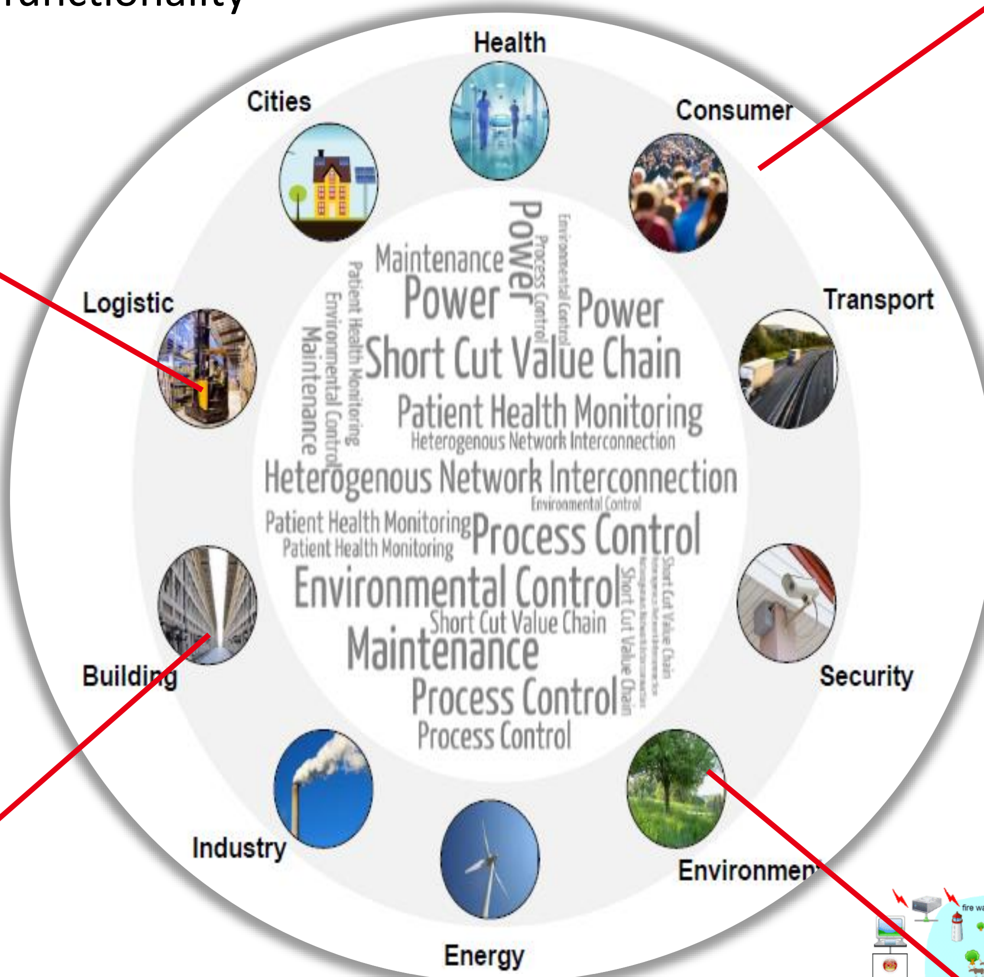
- *The next big Thing in Wireless ? Business Week – 5/12*

A FRAGMENTED MARKET

Specific functionality

Localization of goods in warehouse

Autonomy and precision

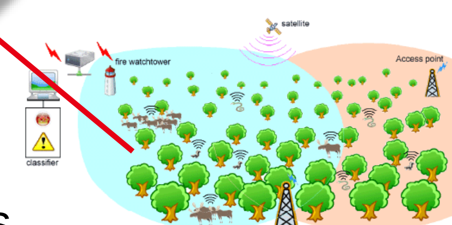


Quantified Self

Multiple products Compatibility

Cost & Density

Fire Detection



A different business model for the ICs

Example : ZigBee Applications

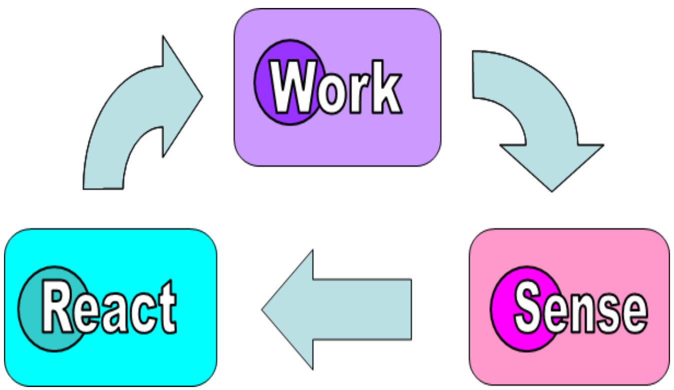
- Example : Schneider
  - Lighting :
    - ++ Standby Power
    - -- sensitivity, communication power
  - Electrical Distribution
    - ++ Sensitivity
    - -- Power
  - Wireless Sensor Network
    - ++ Comunication power
    - + Sensitivity

ZigBee™

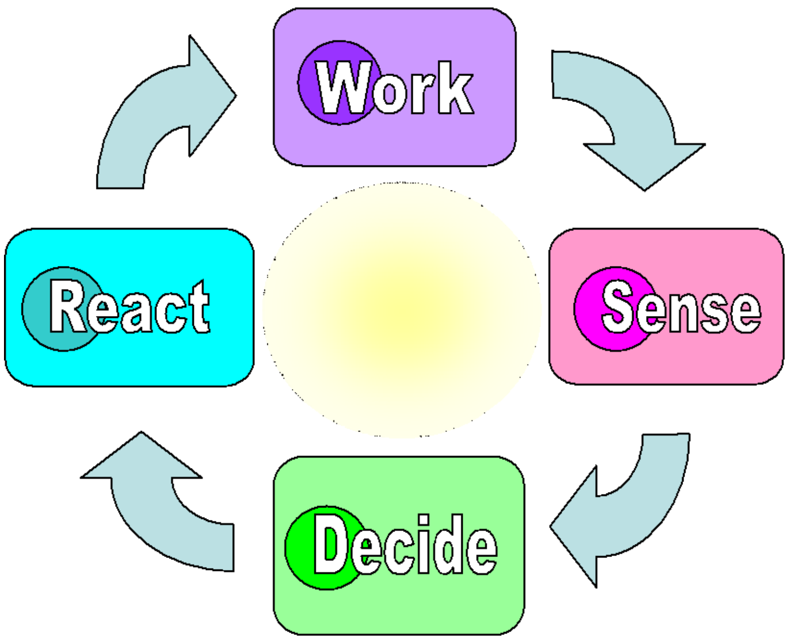
Lower Power

Key Idea : The concept

- Inspired from the Classical (Plan, Do, Check, Act) Deming Wheels



Automatic Control Loop



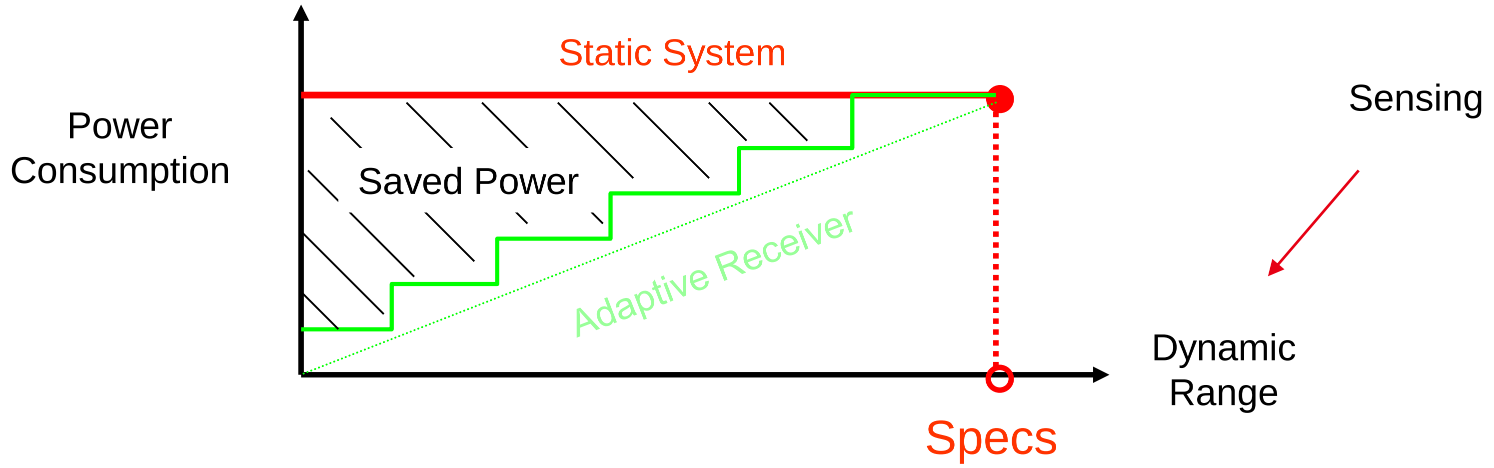
Intelligent Control Loop

EVERYTHING HAS ALREADY BEEN DONE ?

- Automatic Gain Control Loop patented in 1925 and full theoretical analysis in 1928 !!
- Automatic Frequency Control Loop already exploited in the super-heterodyne receiver by British Marconi Radio Technology in 1919 !!

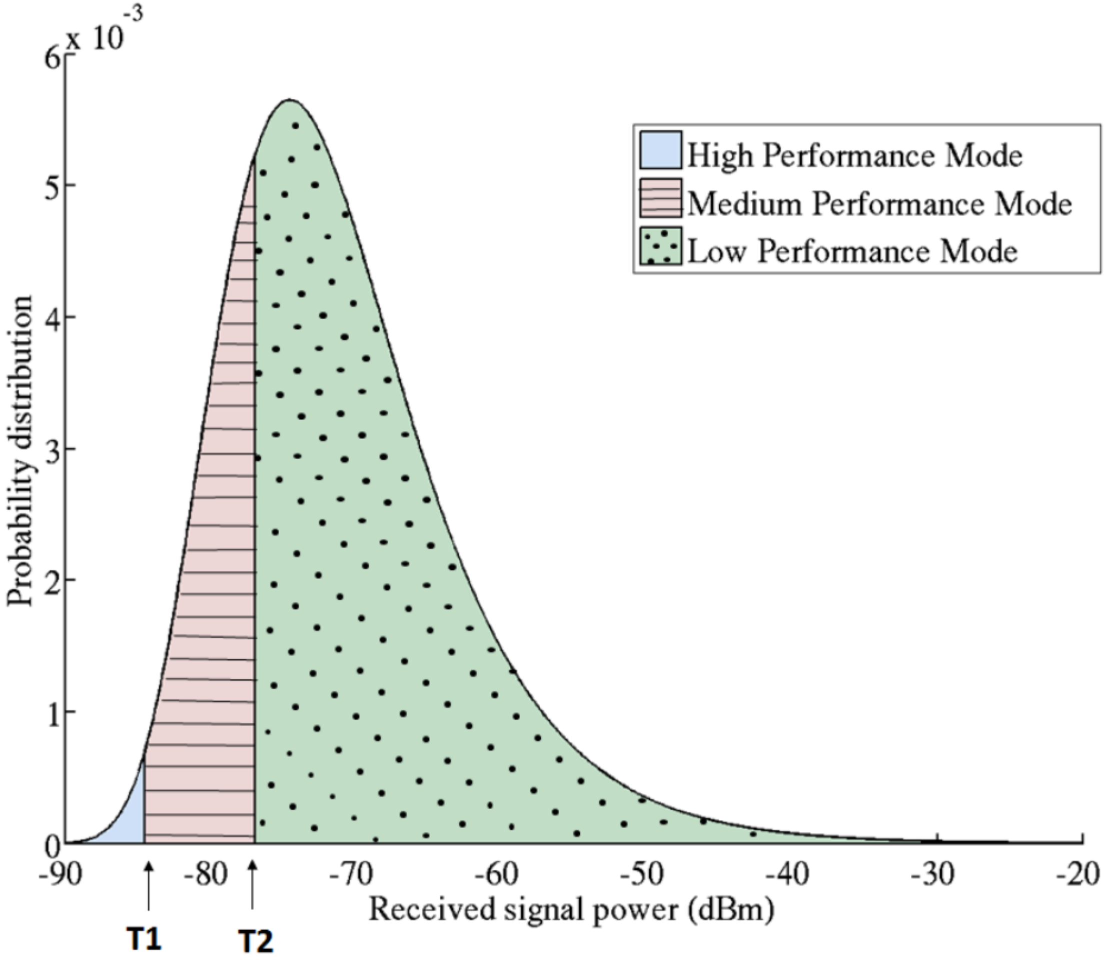
Today

- Existing loops are mainly the mandatory ones and with limited intelligence
- Objective is functionality not power consumption nor energy efficiency



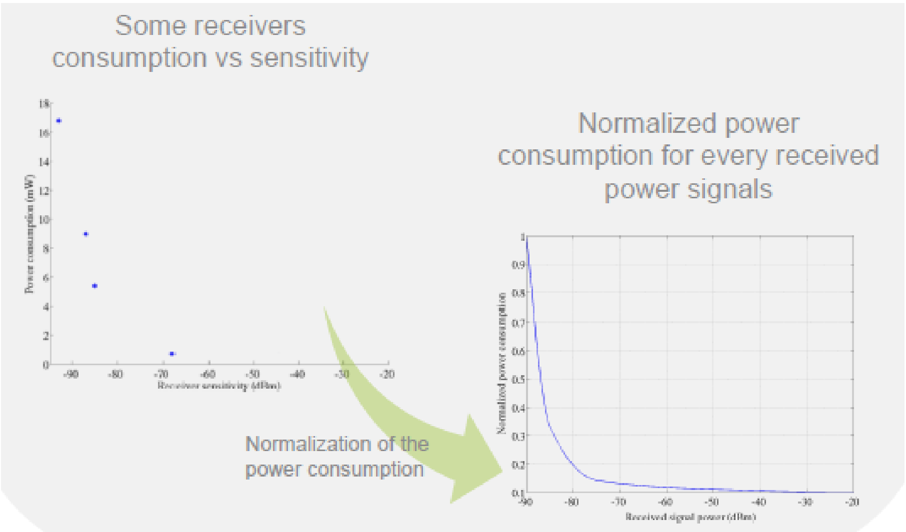
HOW MUCH CAN BE SAVED ?

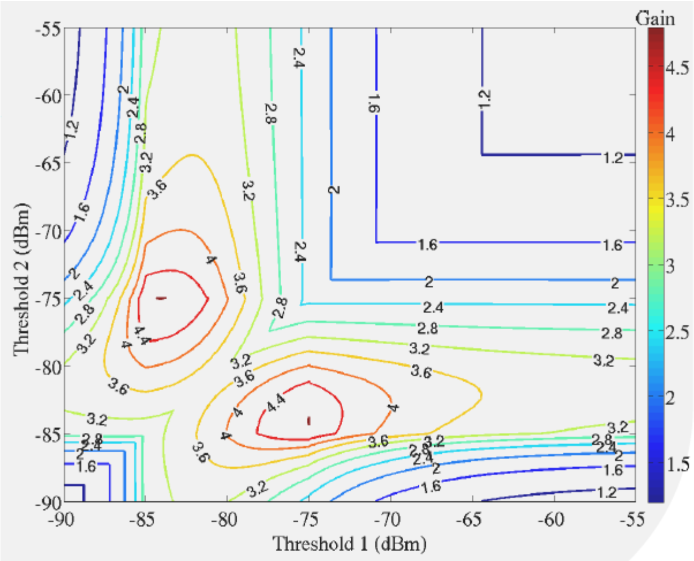
Multi-Level Radio Performances/Power



HOW MUCH CAN BE SAVED ?

Multi-Level Radio Performances/Power





Channel-aware receiver optimization design

Performance Mode	High	Medium	Low
Thresholds (dBm)	-90	-85	-75
Usage time (%)	1	23	76
Normalized power consumption	1	1/3	1/7

Number of modes	1	2	3	4
Number of thresholds	0	1	2	3
Normalized gain on battery lifetime	1	3.5	5	6

MAIN DIFFICULTIES

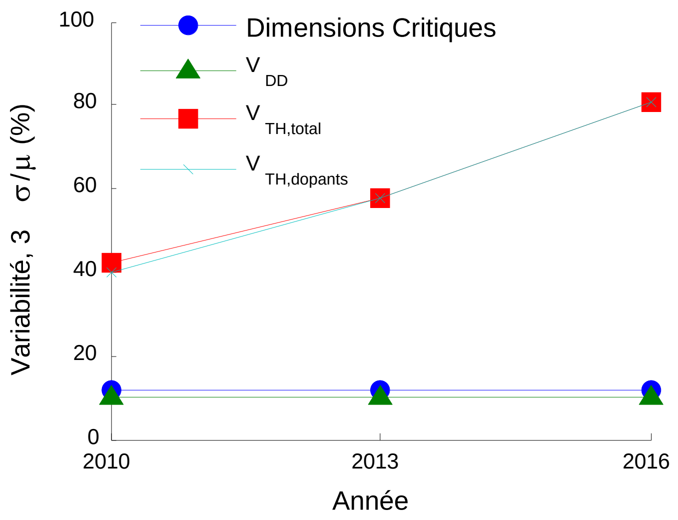
- **Complex Design**
  - Including tunability in Digital-Analog-RF building blocks is not straightforward. It usually increases the power consumption and global area in the standard case !
- **New Marketing**
  - How to commercially valorize such development ? Key figures are usually the extreme case
  - Adaptivity for which application ? No killer application
- **Additional Test**
  - Additional operating points in the system will increase the design (yield)/test complexity and cost of the system
- **Speed**

ADDITIONAL MOTIVATION IS NEEDED

ITRS : Technology Variability :

- Probably the greatest challenge caused by the nano-level scaling is the increase in the intra-die variability of the threshold voltage, drive and leakage current as they become dependent on the statistical distribution of parameters such as physical gate length and dopant concentration.

- Platform architects will have to come up with new methods to design reliable electronic systems with uncertain components, and worst-case design must be avoided. One way to do this is by providing **feedback controllers** that minimize the impact of variability of the individual system components.



Environmental parameters should be also included

WHAT SHOULD BE SENSED ?

Sense

Channel

- Path Loss
- Fading

Statistical

Blockers

- Out of Band signals

Statistical

Technology

- Active
- Passive

Environment

- Temperature
- Voltage
- Battery State

Configuration

- Application
- User Choices
- QoS

Network

CHALLENGES

- Simple, low additional cost (silicon area, power , setup, algorithm, …)
- Sensing with variable precision
- Heterogeneous sensors (system, environment, appli, …)
- No interference on the main sub-systems/function
- May need Fast Sensors and Dynamic Sensors
- Reliability in the sensing procedure (loss of data or errors)
- Distributed Sensing in Systems/Networks
- Event Driven Sensing (latency)

WHICH SENSORS ?

Compromize

Received Signal Characteristics

- Digital Baseband Level
  - rssi

Indirect Sensors

- Temperature
- Bias
- Voltage, Current, Energy (matching)
  - Techno
  - Blockers

Processing Complexity

Sensor Cost

Direct Sensors

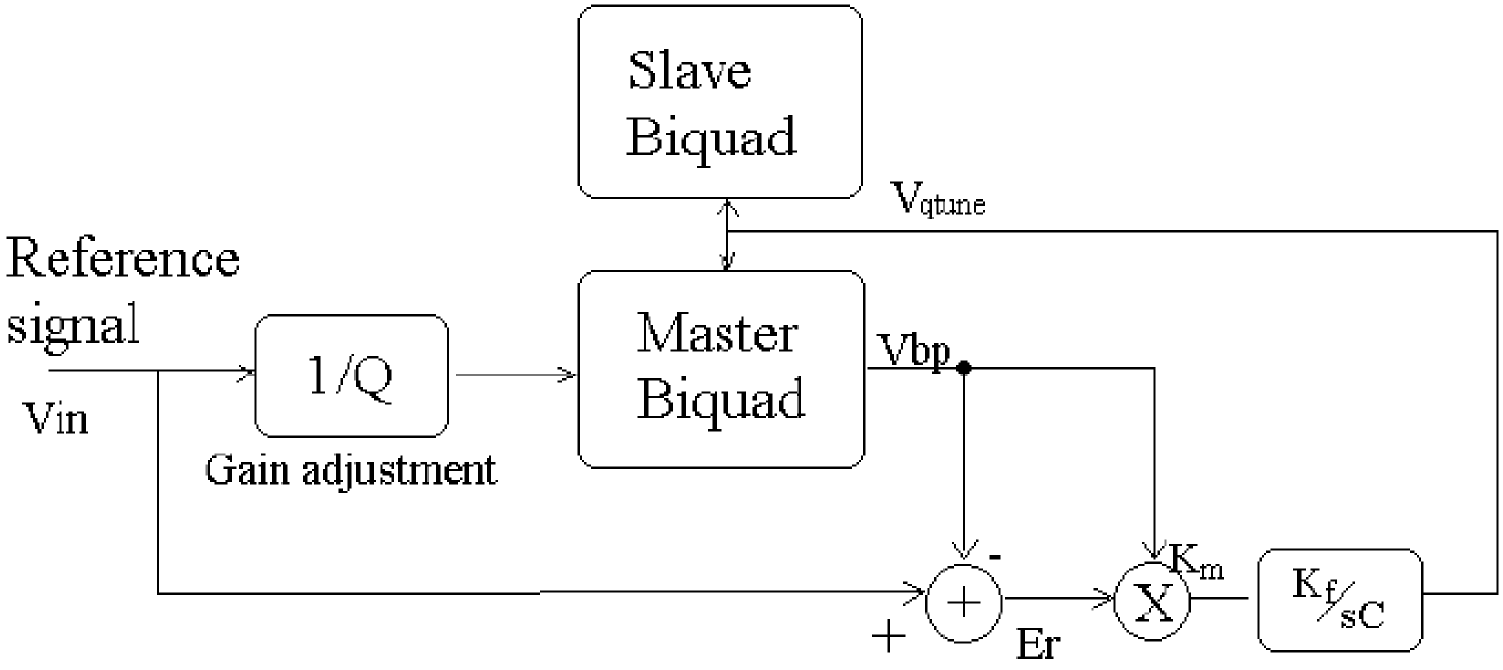
- Voltage, Current, Energy of the signal (! load)

Architecture Modification

- Block Architecture (Intermediate node in Biquad, ADCs, …)
- Additional Components in the main path (C,L, …)
- Deeply modified architecture : additional receiver
  - Precise Phenomena
  - Blockers

Without Processing :

Master/slave filter tuning

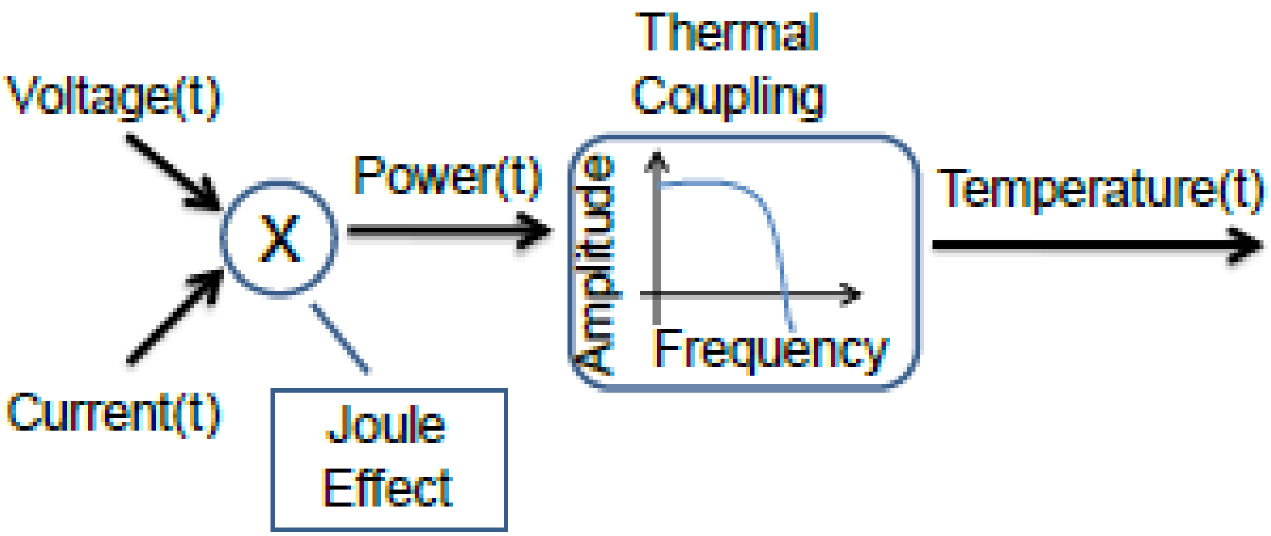


Ref: K.S. Tan and P.R. Gray, “Fully integrated analog filters using bipolar FET technology,” IEEE, J. Solid-State Circuits, vol. SC-13, no.6, pp. 814-821, December 1978..

SOTA – Indirect Sensing

With Processing :

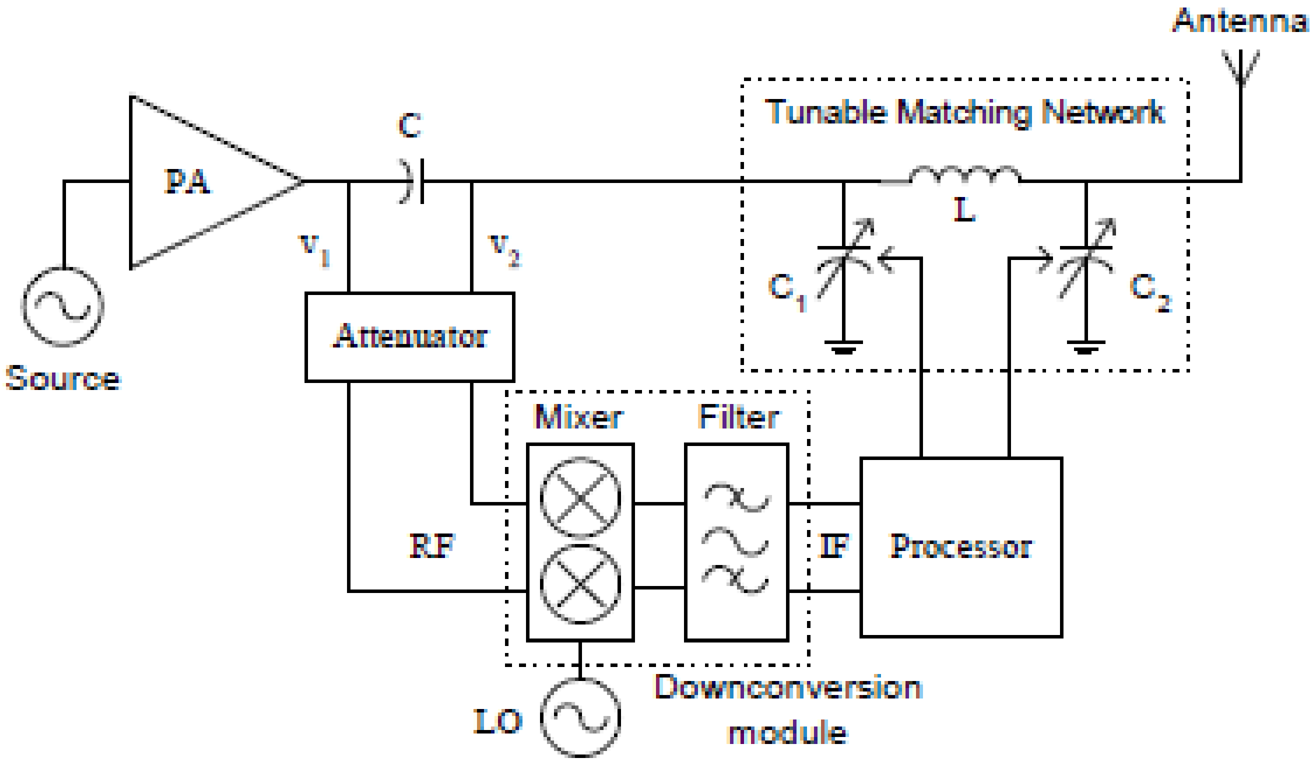
Signal Test through temperature evaluation



Gonzalez, J.L.; Martineau, B.; Mateo, D.; Altet, J. «Non-invasive monitoring of CMOS power amplifiers operating at RF and mmW Frequencies using an on-chip thermal sensor » IEEE RFIC 2011; pp. 1 - 4

Dedicated extraction chain

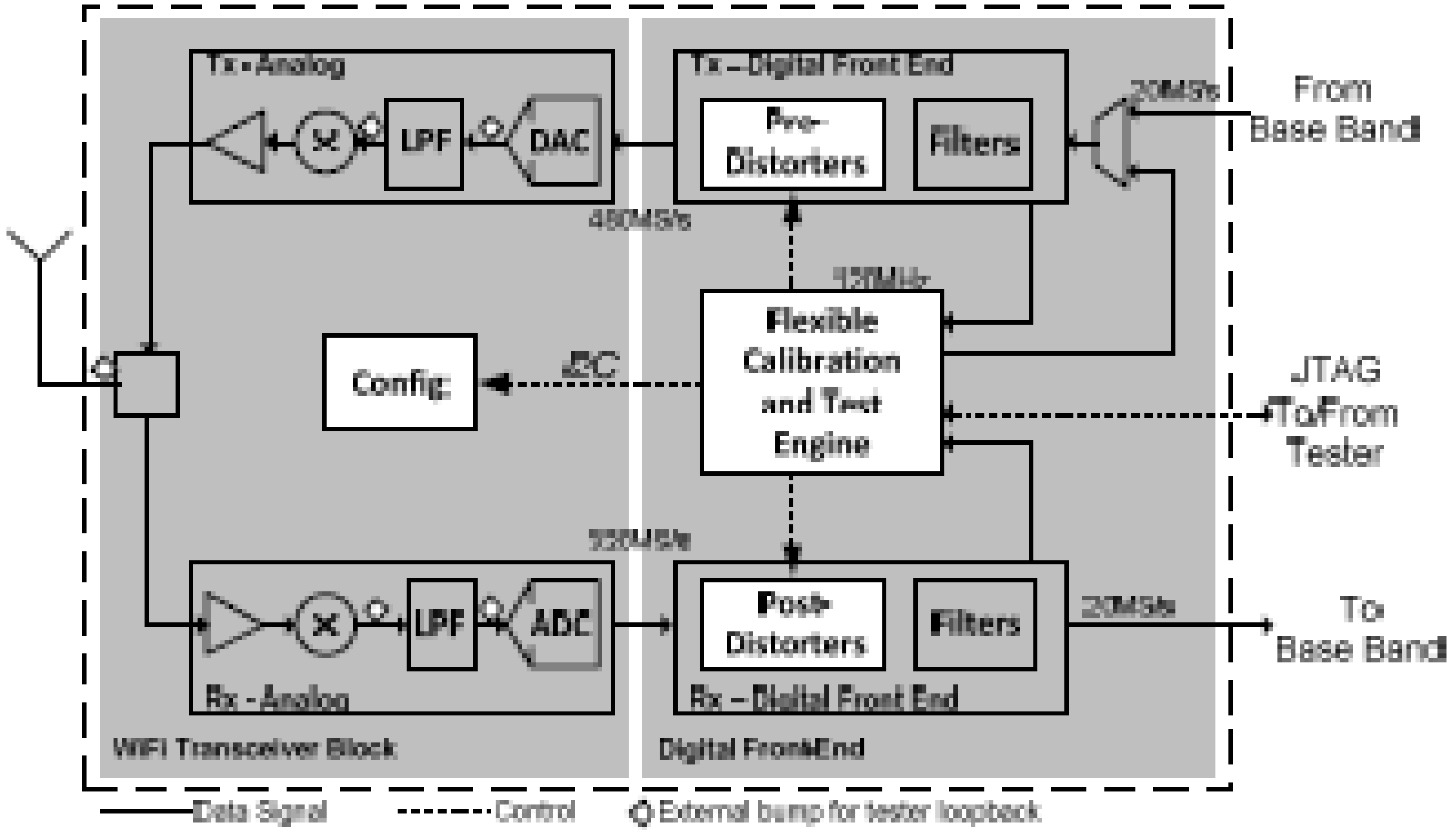
Automatic matching system



Wai Chan; De Foucauld, E « A fast and accurate automatic matching network designed for ultra low power medical applications » ISCAS 2009, Page(s): 673 - 676

SOTA – Direct Sensing

From the main chain

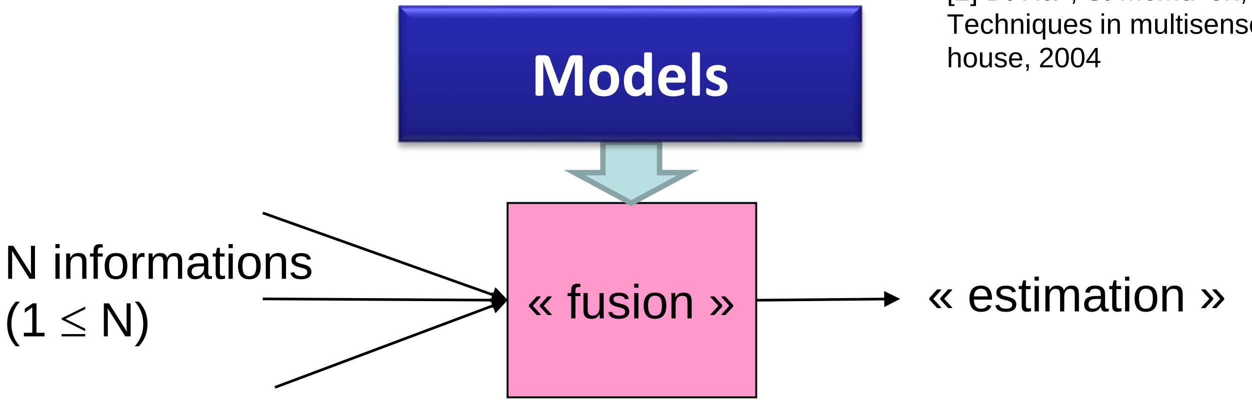


J. Hermosillo*, J. Carballido*, et al. « A Programmable Calibration/BIST Engine for RF/Analog Blocks in SoCs » IEEE ESSCIRC 2012 pp. 133-136

DATA MINING

- Data fusion : « integration of information from multiple sources to produce specific and comprehensive unified data about an entity »
- Modeling is key

[1] M. Liggins , D. Hall , J. Llinas, Handbook of Multisensor Data Fusion", CRC press, 2nd edition, 2008.
[2] D. Hall, S. McMullen, « Mathematical Techniques in multisensor Data Fusion », Artech house, 2004



CHALLENGES : OPTIMIZATION

Decide

On-line Optimization

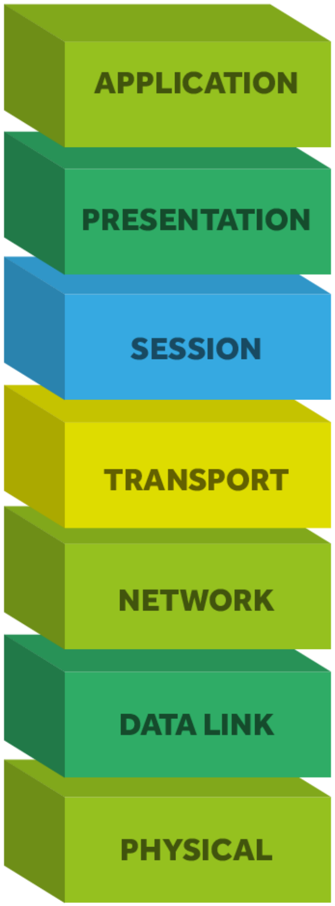
- Convergence to the optimal point ?
  - Local/global minimum
- Development of low added complexity optimization algorithm
- Cross-Layer communication : standardisation ?

- **Robustness** in the decision procedure (loss of datas or errors and latency)

Elaboration of the cost function at system level

- Multi-criteria, Multi-Constraints optimisation
  - Power, Energy, QoS, …
- Consider system performances and not the blocks

GLOBAL EVALUATION OF THE APPROACHES

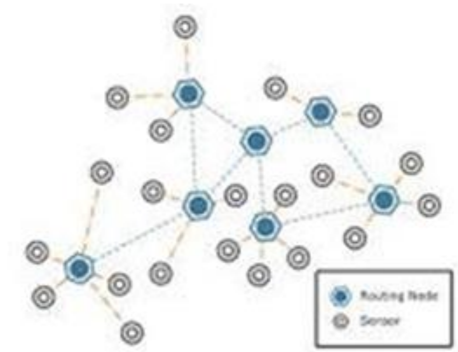


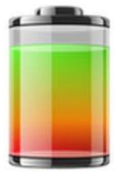
Network Simulator

ns-3 NETWORK SIMULATOR

WSNet

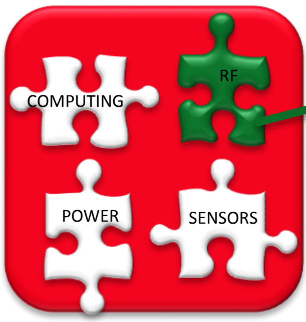
Optimization

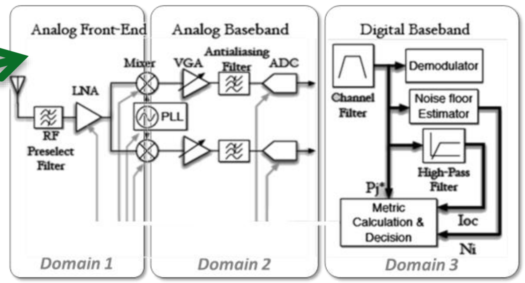


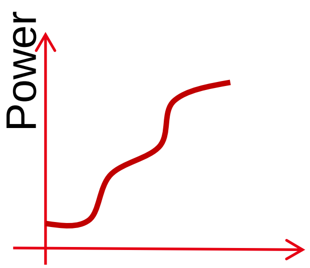


IoT Application (QoS)

Power Models







CHALLENGES

- **Development of tunable and power efficient building blocks**

  - Difficulty to tune the block characteristics independently from each other in Analog/RF building blocks
  - Architecture reconfiguration may be needed for wide range
  - Power consumption of secondary blocks (i.e. buffers), negligible at high resolution, usually becomes significant when tuning the power

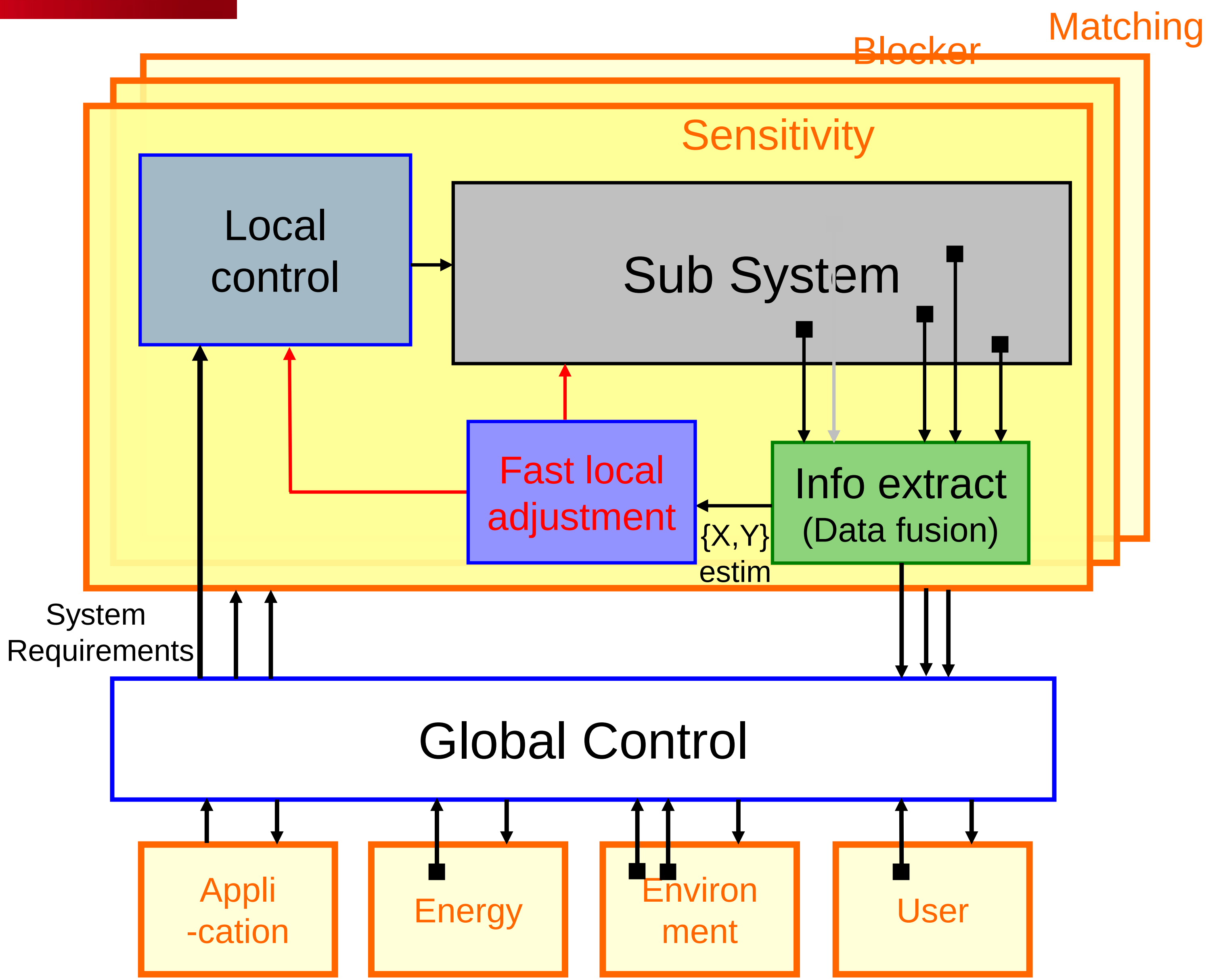
- **Off-line Optimization**

- **Transient in the Control Loop while toggling**

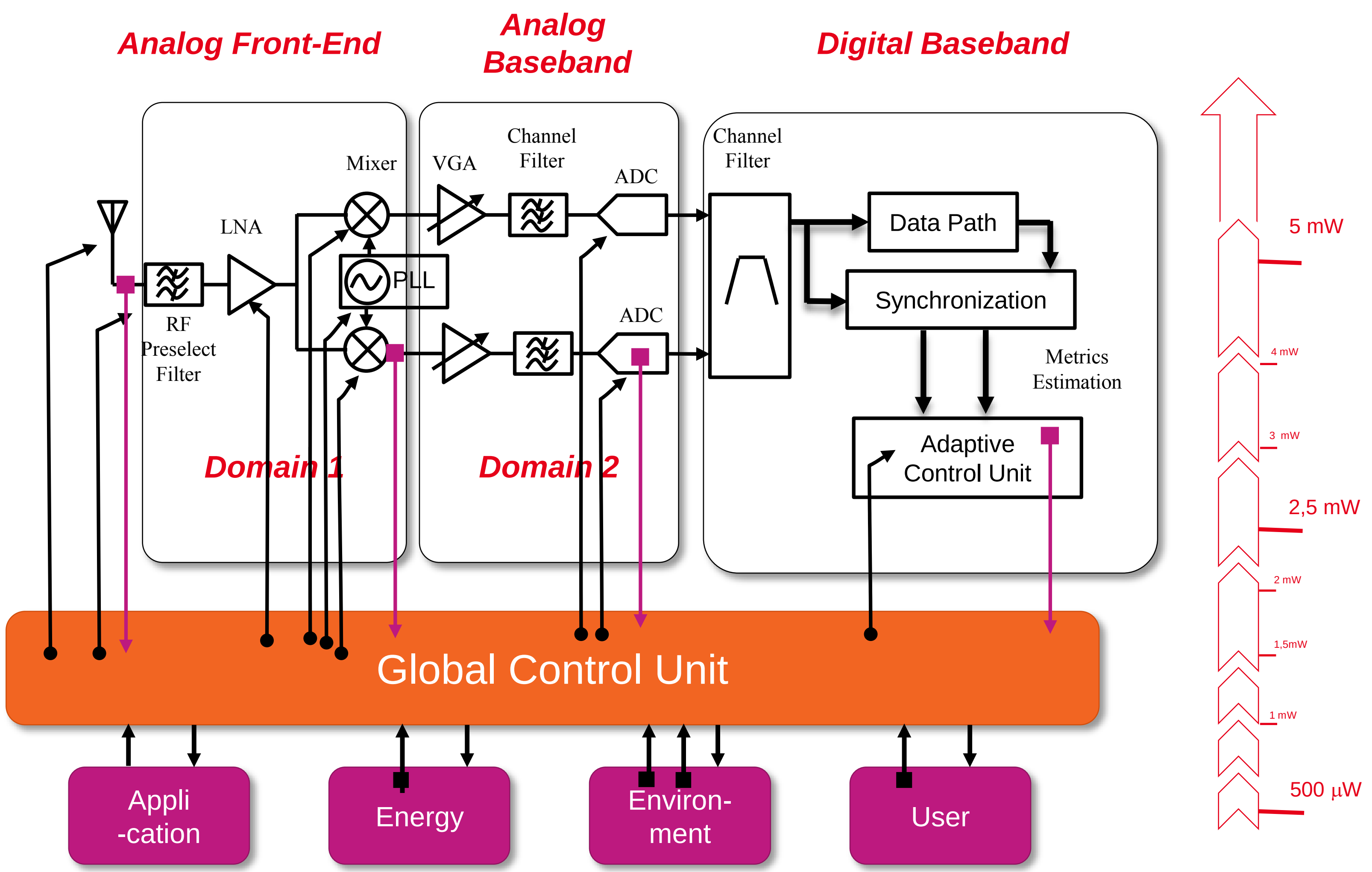
  - Prevent unstable state during transient (Hybrid System Theory)
  - Speed, Energy/Power Constraints
  - One step/multistep transient

GENERAL S&R ARCHITECTURE

React

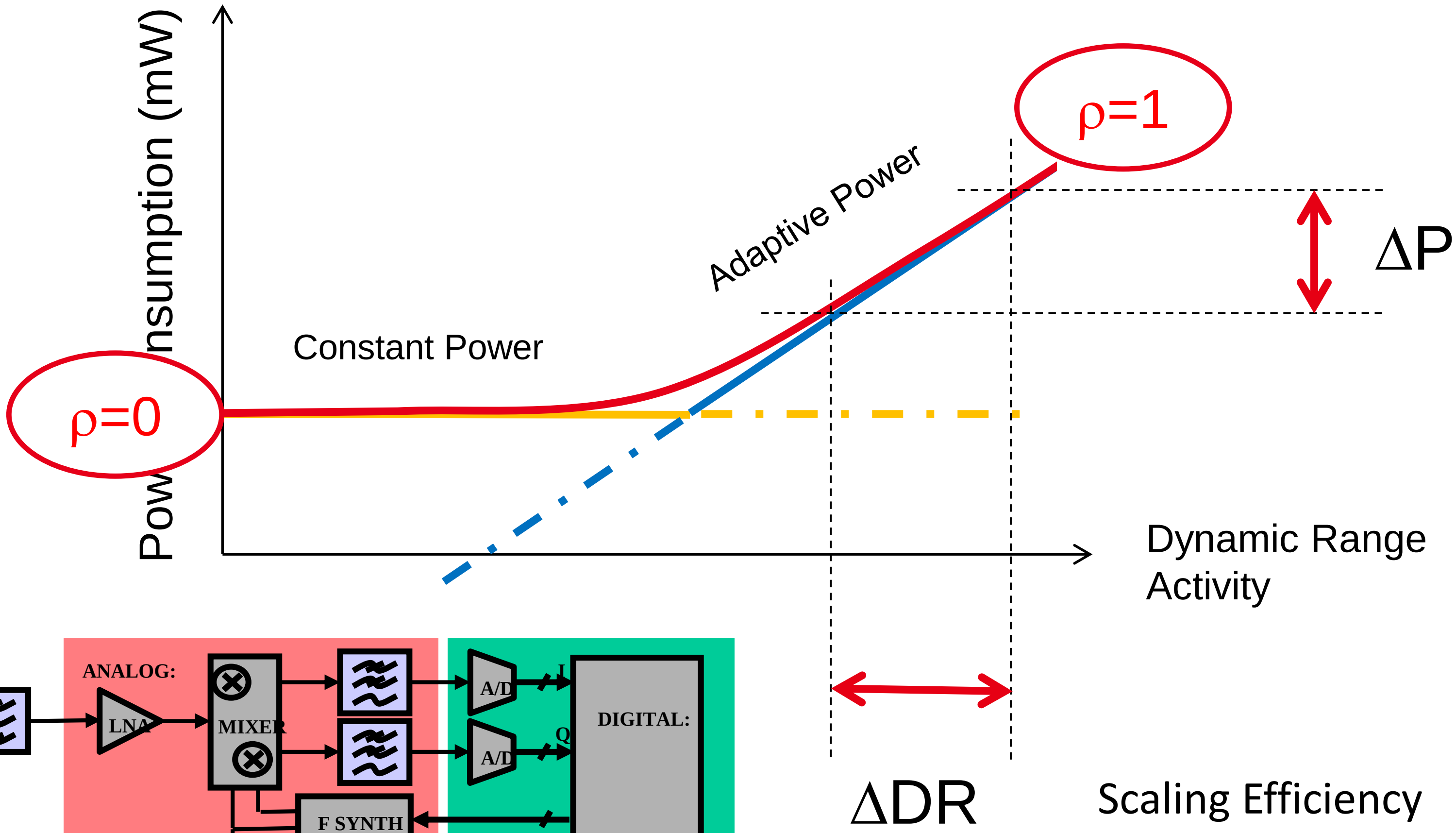


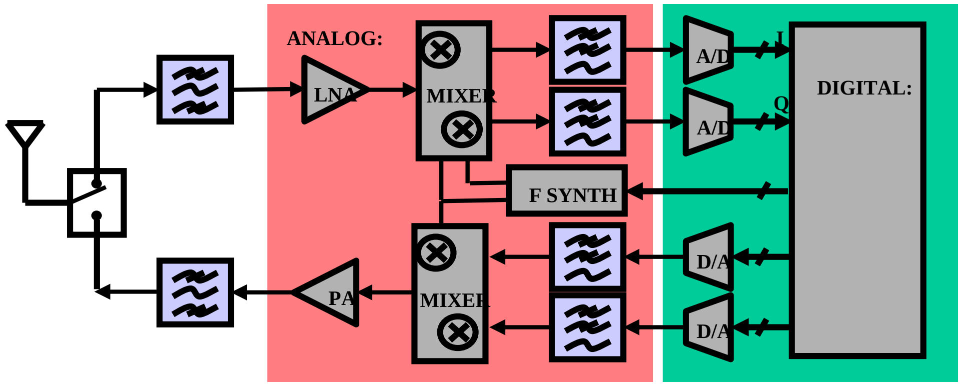
SIMPLIFIED RECEIVER IMPLEMENTATION



POWER SCALING BOTTLENECK

General Power Scaling Rule



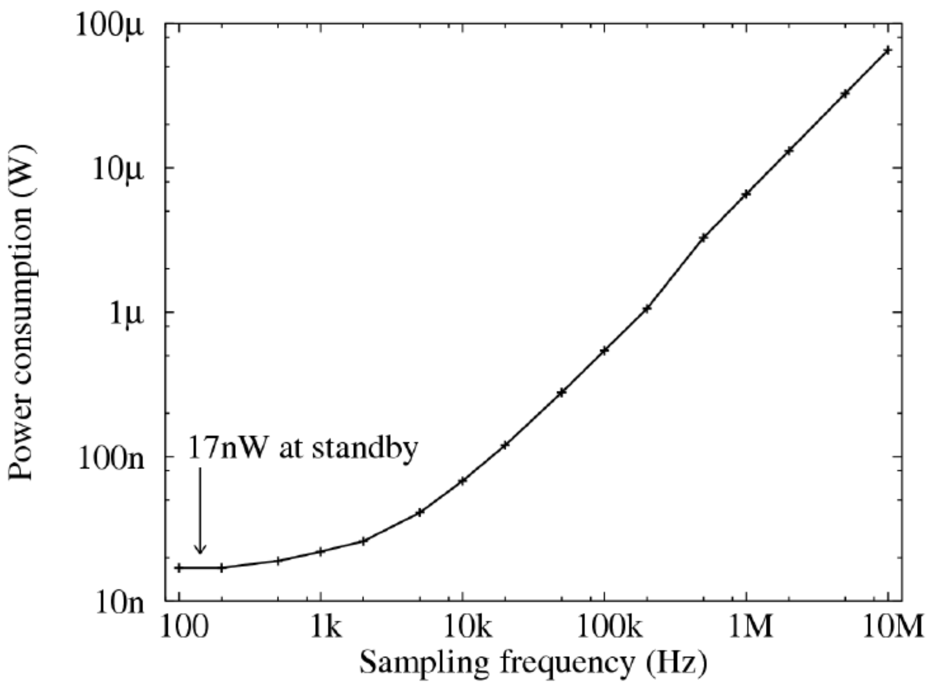


Scaling Efficiency

$$\rho \triangleq \frac{\Delta P\ (dB)}{\Delta DR\ (dB)}$$

FLEXIBLE BUILDING BLOCKS : IN TIME

Analog to Digital Converter



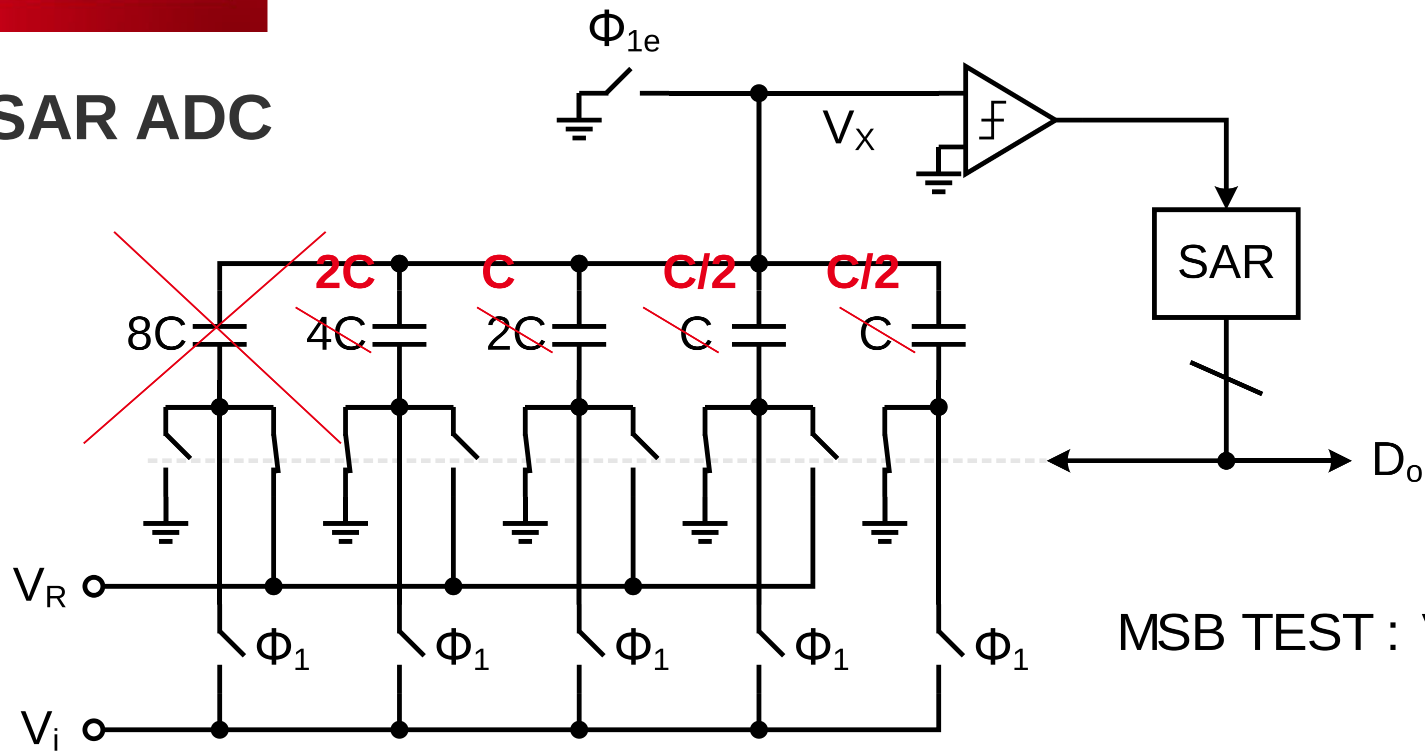
[Harpe2010]

☺ Wide Scaling Range with good efficiency

☹ No Energy Reduction / operation

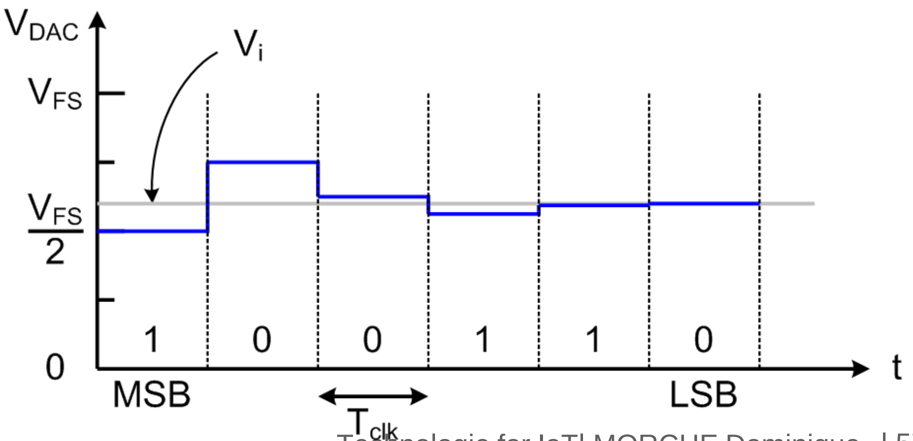
FLEXIBLE BUILDING BLOCKS : IN DYNAMIC RANGE

SAR ADC

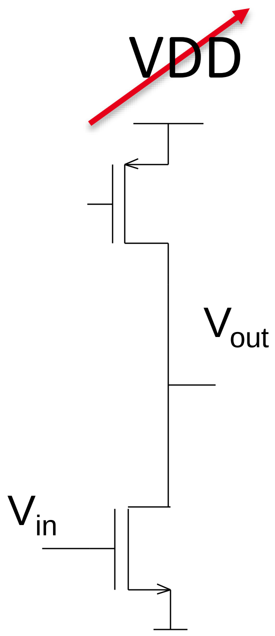


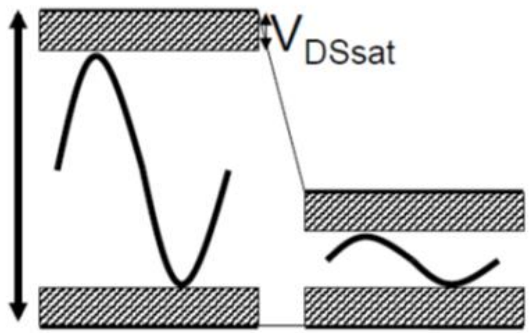
MSB TEST : $V_X = \frac{V_R}{2} - V_i$

Thermal noise : kT/C



FLEXIBLE BUILDING BLOCKS (VOLTAGE)

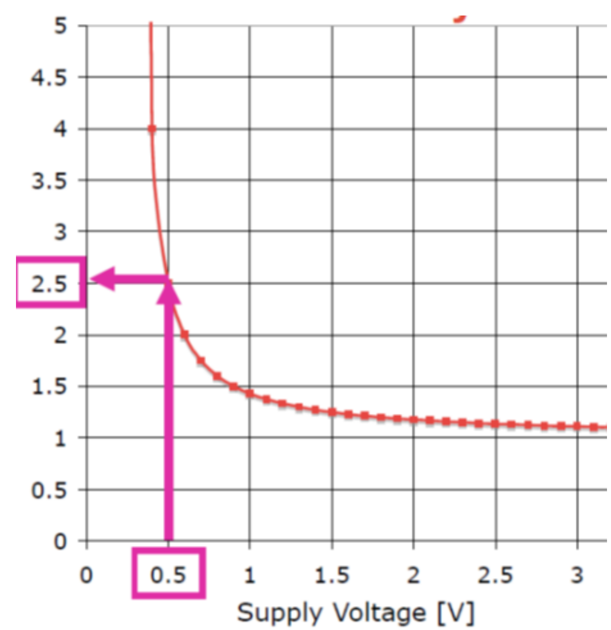




Power = VDD*I

Vin= VDD-2VDSAT

ρ



Power = VDD*I

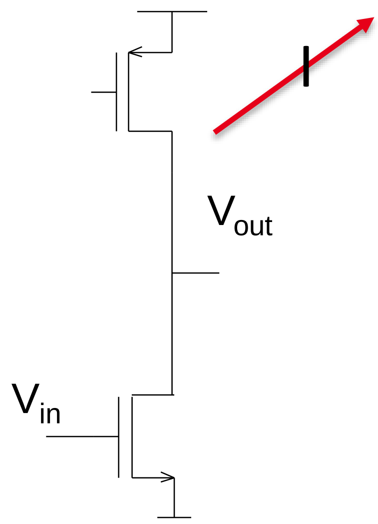
VIN= VDD

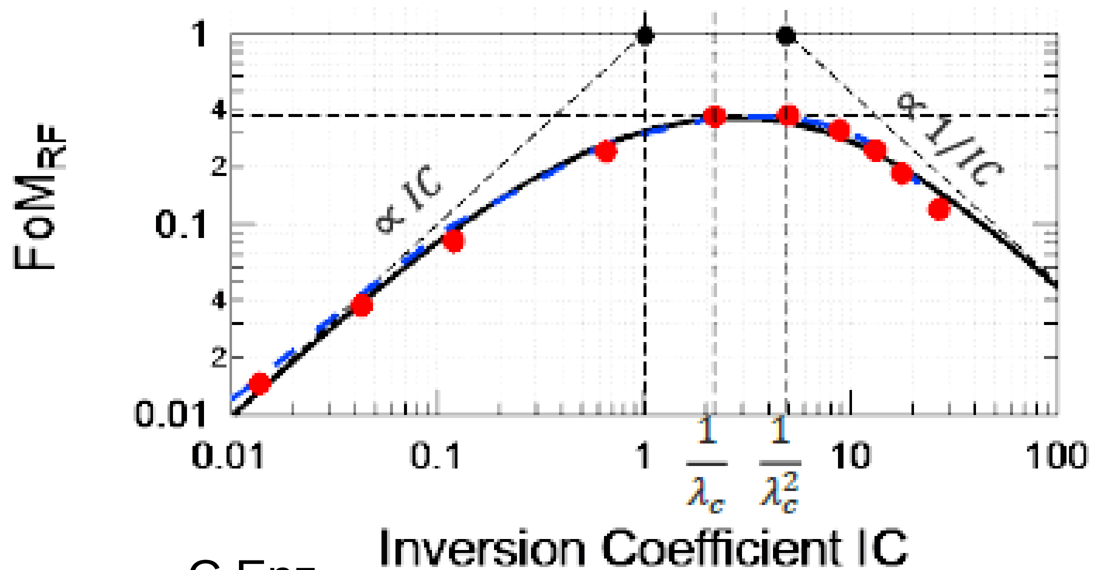
ρ=1

FLEXIBLE BUILDING BLOCKS (CURRENT)

$$IC = \frac{I_D}{I_{spec}}$$

$$FoM = \frac{Av_{abs}.freq_{GHz}}{(F_{min}-1)_{abs}.(I_D.Vdd)_{mW}}$$





Power = VDD*I

VIN= k.I

ρ=1

C.Enz

Which efficiency ?

Example Swap **DR (Dynamic Range)** for **P** (Power)

Efficiency definition : $\rho \triangleq \dfrac{\Delta P\ (dB)}{\Delta DR\ (dB)}$

	Circuit	**ΔDR**	**ΔP**	**ρ**
[Yoshizawa2007]	Filter	19,9 dB	3,5 dB	0,175
[Ozgun2006]	Filter	29,9 dB	7,6 dB	0,254
[Harpe2012]	ADC	18 dB	3 dB	0,166
[Malla2008]	ADC	18,0 dB	3,9 dB	0,216
[Verma2007]	ADC	24,0 dB	1,7 dB	0,071
[Aust2001]	ADC	12,0 dB	0,5 dB	0,042

- The scaling ranges are limited
- The reconfiguration factors are low indicating inefficient scaling

RECONFIGURABLE TRANSCEIVERS : SOTA

CC2500

- Transmitter

Current Consumption	TX power
11,1 mA	-12 dBm
15,0 mA	-6 dBm
21,2 mA	0 dBm
21,5 mA	+1 dBm

CC2500

- Receiver

Current Consumption	Symbol rate
17,0 mA	2.4 kBaud
17,3 mA	10 kBaud
18,8 mA	250 kBaud
19,6 mA	500 kBaud

BlueNRG

Current Consumption	TX power
11 mA	5 dBm
8,2 mA	0 dBm
7,2 mA	-2 dBm
6,7 mA	-6 dBm
6,3 mA	-9 dBm
6,1 mA	-12 dBm
5,9 mA	-15 dBm
5,8 mA	-18 dBm

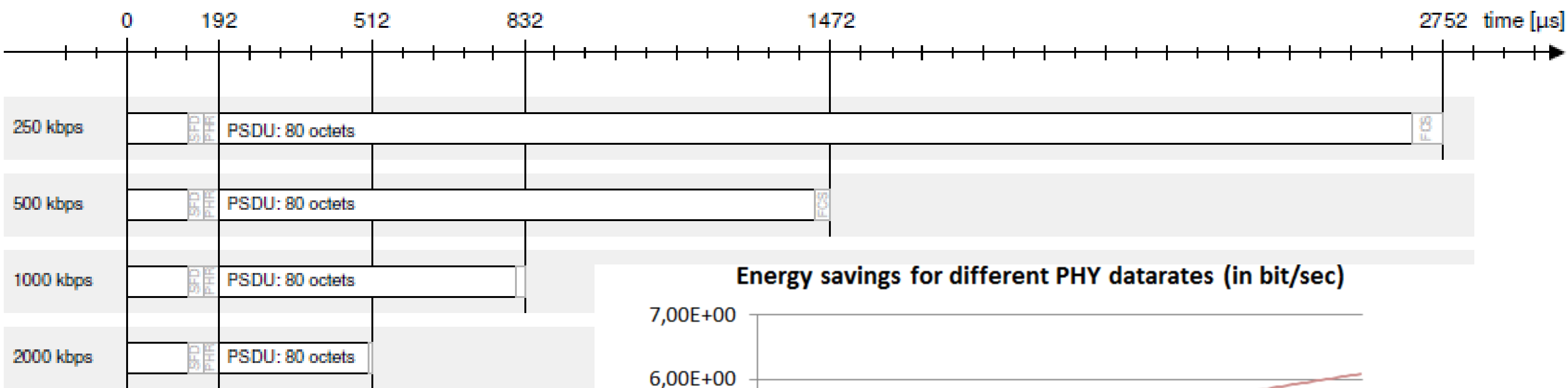
➡ **Poor Power Flexibility**

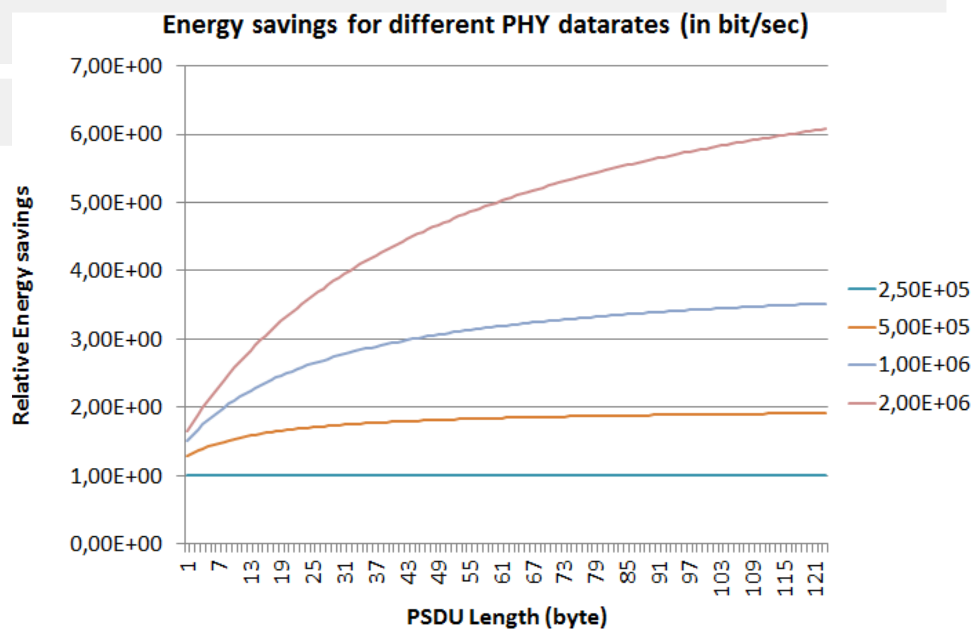
SCALE THE DATA-RATE

AT86RF233

Atmel

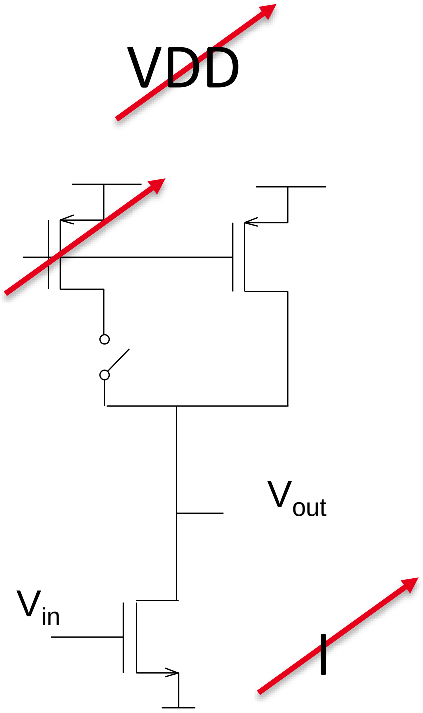
High Data Rate	Sensitivity	Comment
250kb/s	-101dBm	PER ≤ 1%, PSDU length of 20 octets
500kb/s	-96dBm	PER ≤ 1%, PSDU length of 20 octets
1000kb/s	-94dBm	PER ≤ 1%, PSDU length of 20 octets
2000kb/s	-88dBm	PER ≤ 1%, PSDU length of 20 octets





Scale Analog power with Digital

FLEXIBLE BUILDING BLOCKS IMPROVEMENT

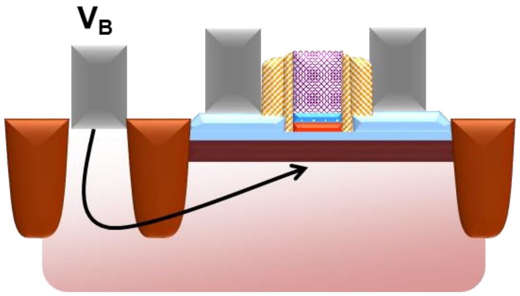


Parasitics !

+ additionnal functionalities

- Gain boosting
- Noise canceling
- Linearisation
- …

Acitvated or not



FD-SOI

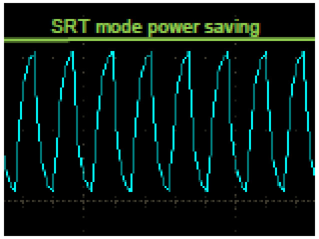
NEW RECONFIGURATION MODE

SMART POWER REDUCTION TECHNIQUES

AT86RF233

- **PLL Energy Saving Mode (PES) :**
  - the power consumed in PLL_ON state reduces from 5.2mA typically to 450mA
  - Only in transient phases

- **Smart Receiving Technology (SRT)**
  - 50 %power consumption by periodically enabling and disabling the transceiver while listening for incoming frame
  - 1dB loss in sensitivity



- **Extended Receiver Desensitizing (ERD)**
  - Min sensitivity : -101dBm@11mA
  - Tunable Receiver from -91dBm@10,5mA to -49dBm@8,5mA

CONCLUSION ON ADAPTIVE RADIO

- ADAPTATION POWER IS ALREADY IMPLEMENTED
  - Limited Range available
  - Efficiency is limited

- PHYSICAL CONSTRAINTS IMPACT THE SCALING EFFICIENCY
  - Especially in the analog domain

- NEW TECHNOLOGIES AND TECHNIQUES MAY IMPROVE THINGS
  - FD-SOI
  - Compensation Loop (Digital)
  - Dedicated Standard / adapted MAC

- TODAY, BEST ADAPTATION DIRECTION IS THE TIME
  - New signal approaches ?

PRESENTATION OUTLINE

1. **Introduction and Prerequisites**

2. **Adaptive Radio**

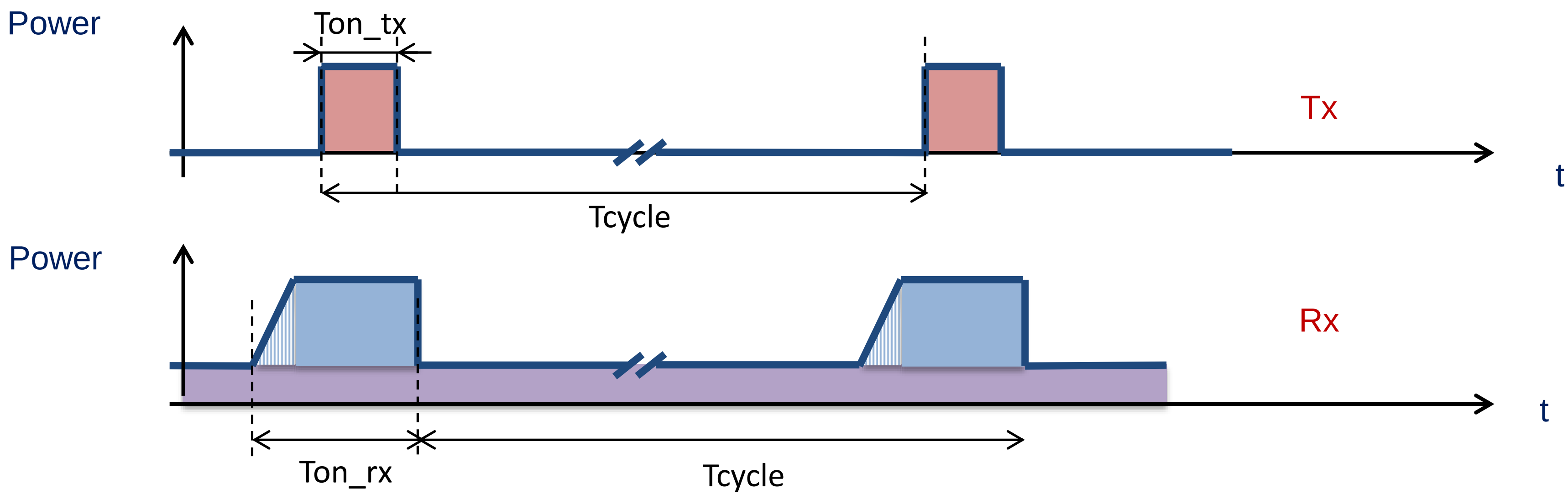
3. **Wake-Up Radio**
   - Motivation
   - Different Approaches
   - Existing Architecture & Solution
   - Extension of the concept

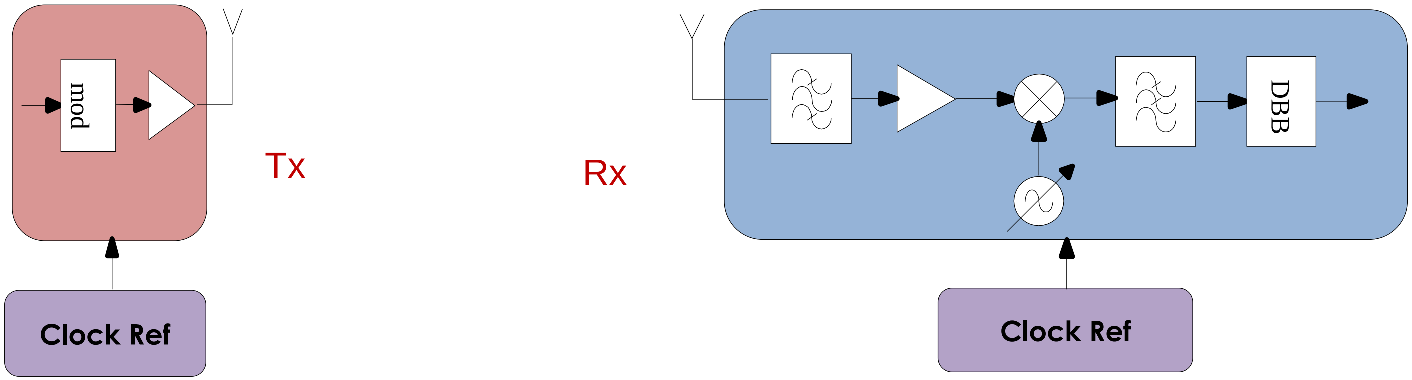
4. **Ultra-Narrow-Band Approach**

DUTY CYCLE

Basic Principle

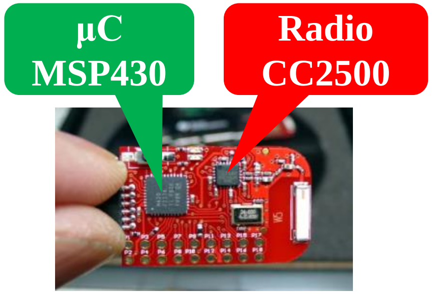
$$duty\ cycle = \frac{Ton\_rx}{Tcycle}$$



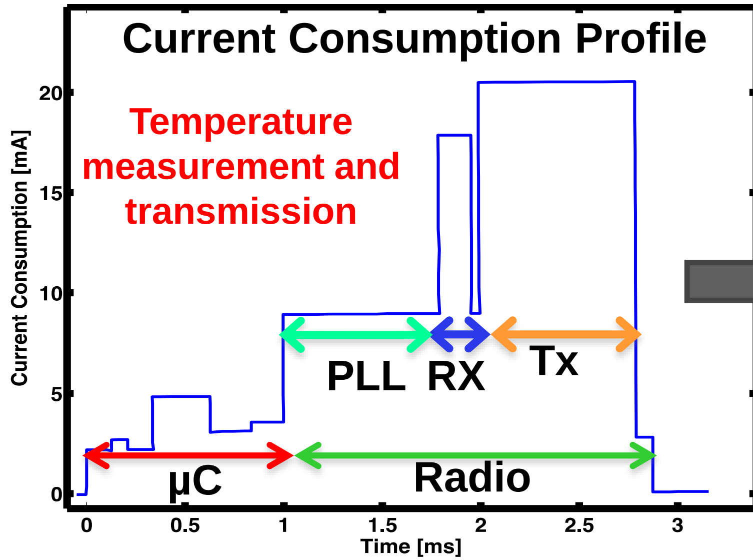


DUTY CYCLE BENEFIT

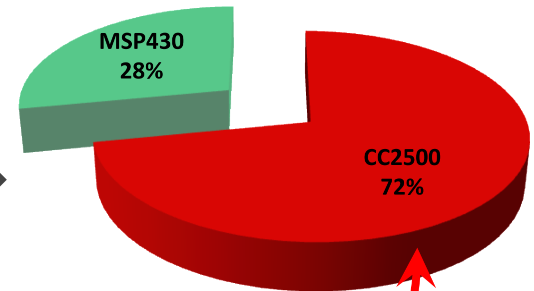
- **Use case: eZ430-RF2500 sensor node**



eZ430-RF2500
(Texas Instruments)



Energy Consumption of the MSP430 and CC2500



Large power consumption

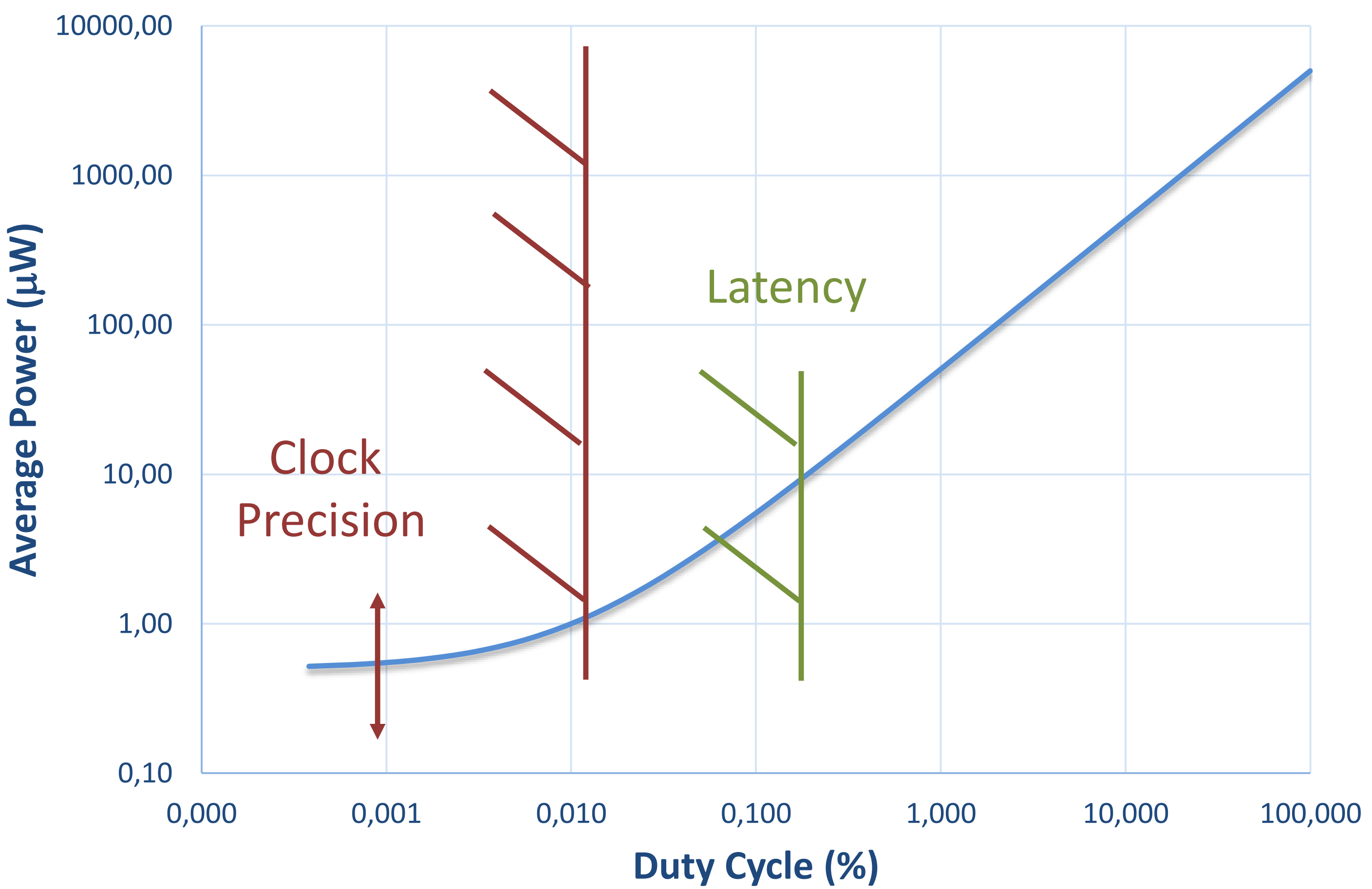
- Lifetime estimation using a 400mAh battery
  - Continuous sensing : < 2 days
  - Duty-cycle of 1s : ~ 1.5 year
  - Duty-cycle of 5s : ~ 5.5 years

< target lifetime: more than 10 years without battery replacement!

Many applications may not tolerate a high duty-cycle

DUTY CYCLE : POWER EVOLUTION

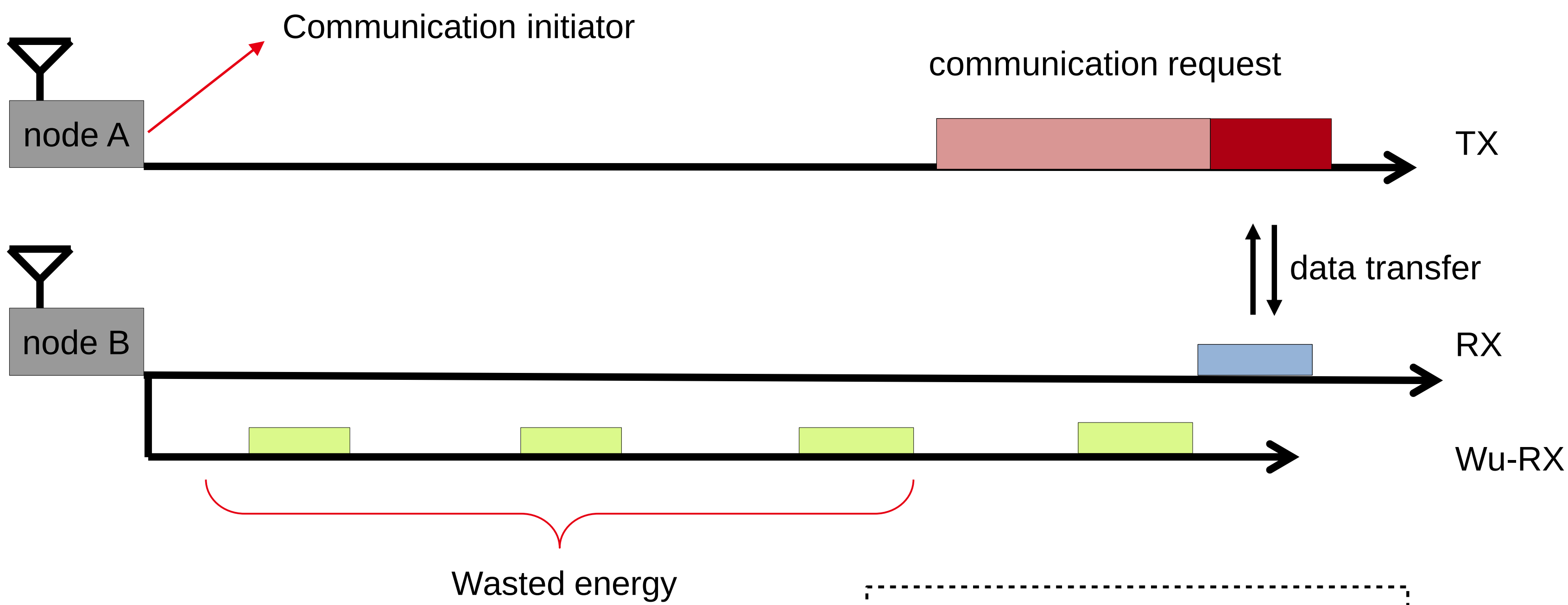
Duty Cycle Limits

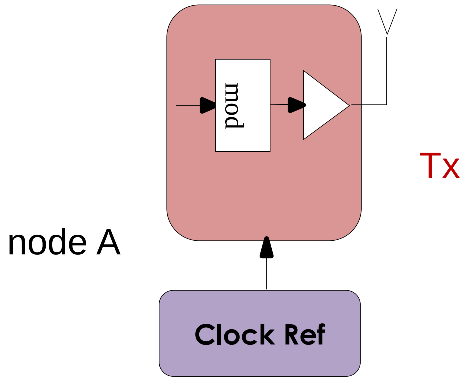


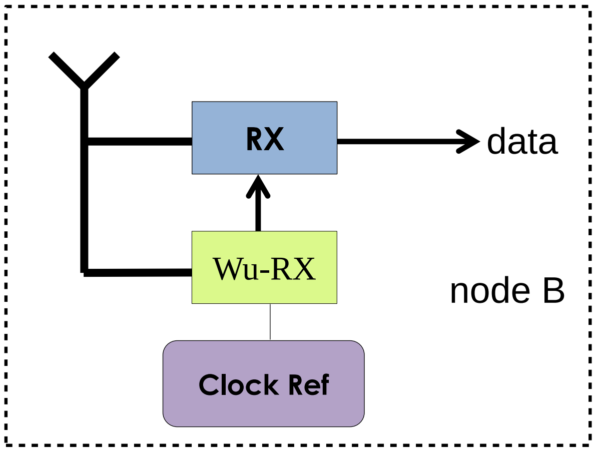
+ Connection Power

WAKE-UP RADIO CONTEXT : 1

Scenario 1 : listening node

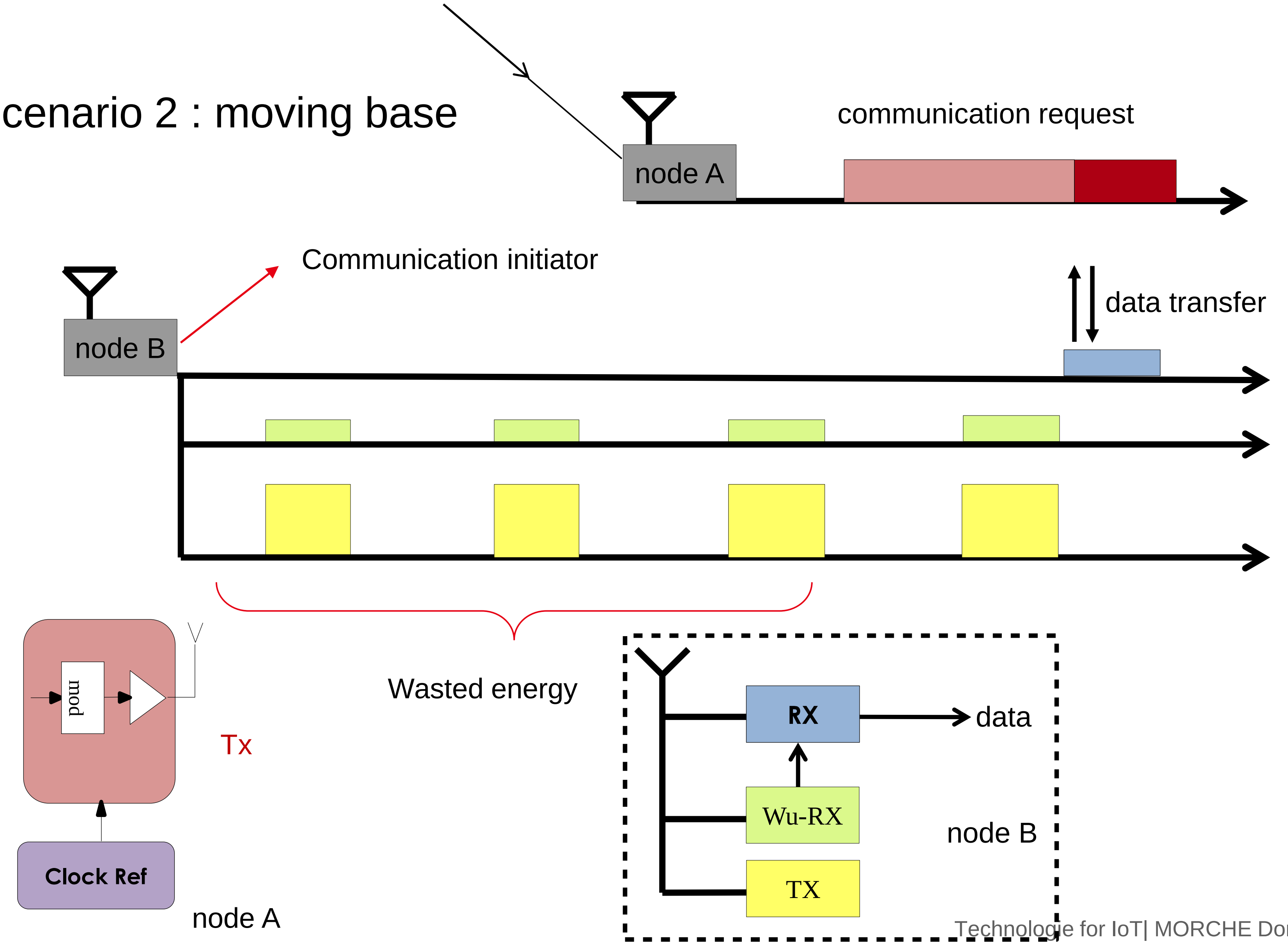






WAKE-UP RADIO CONTEXT : 2

Scenario 2 : moving base



WHICH RADIO FOR THE WAKE-UP ?

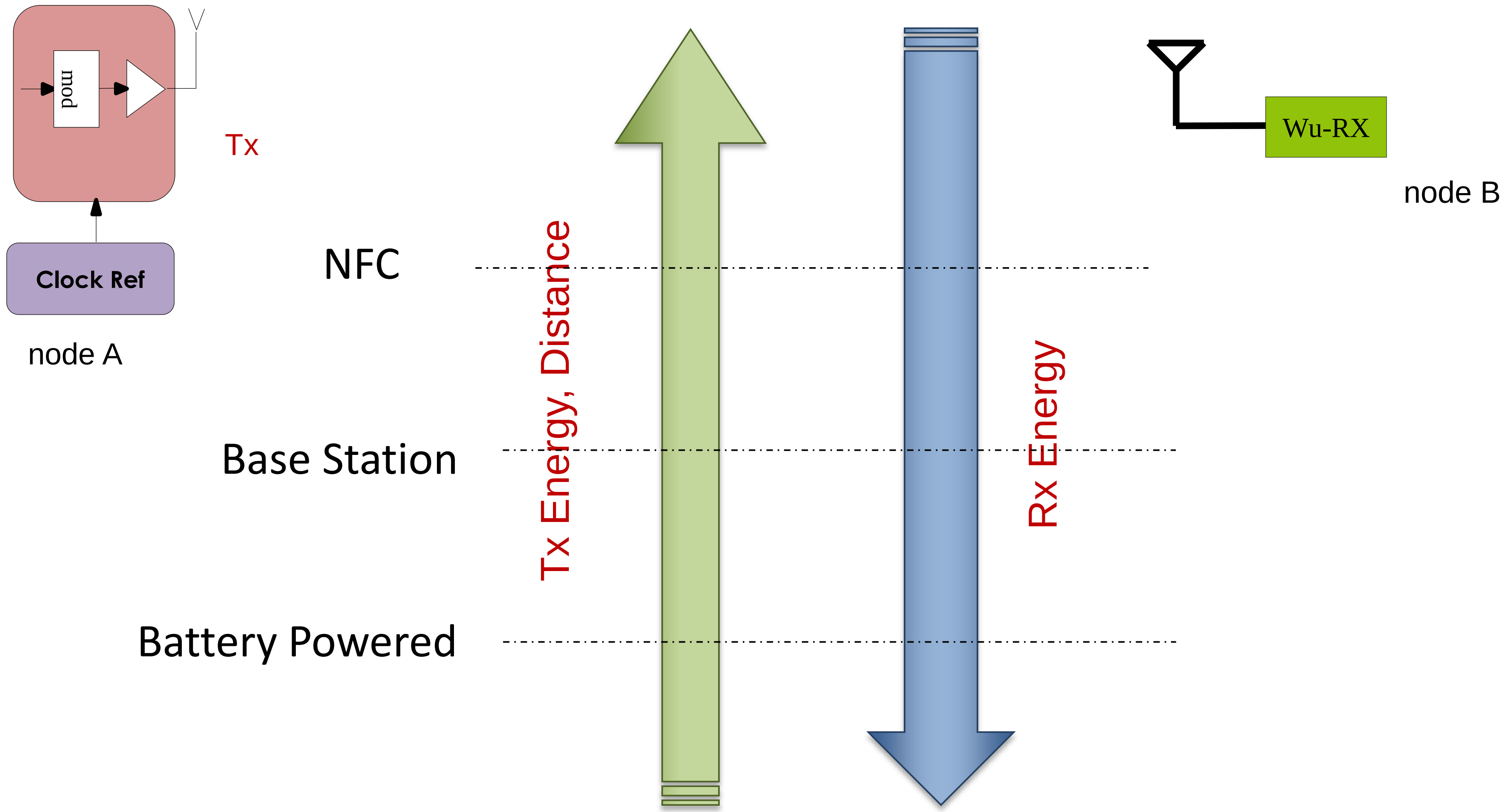
DIFFERENTIATOR	Wu-RX <<< RX
Simplified modulation	• Simple Baseband (-50%) • Poor tunability
Simplified front-end	• Degraded Robustness to Blockers • Limited Range

Reduced QoS

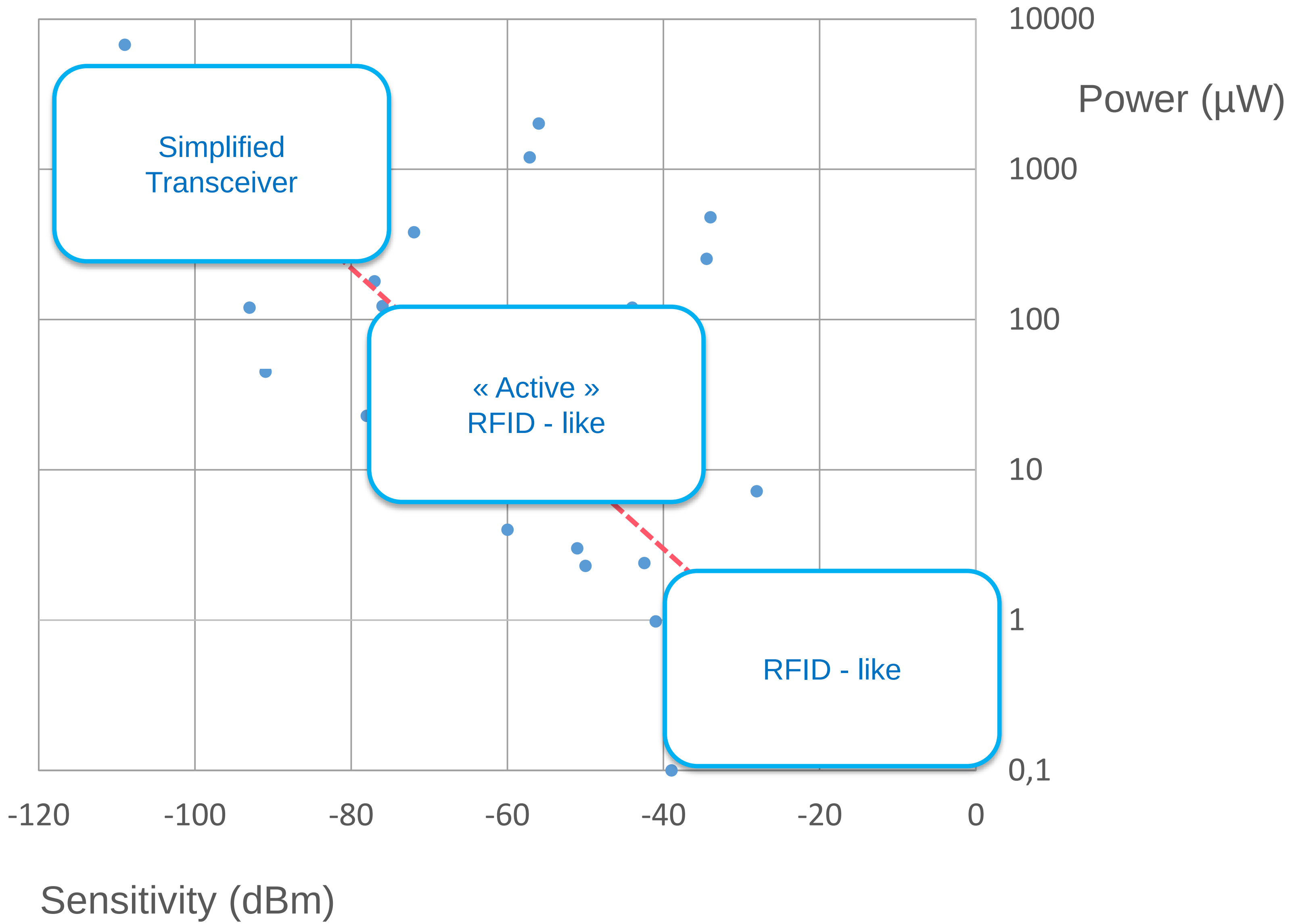
Specific scenario
Secondary message

SCENARIO 2 : ASYMMETRICAL LINK

- Wide Range of Applications

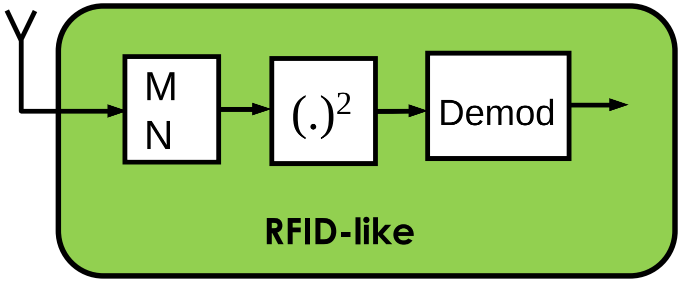


WAKEUP RADIO STATE OF THE ART



RFID-LIKE WAKE-UP RADIO

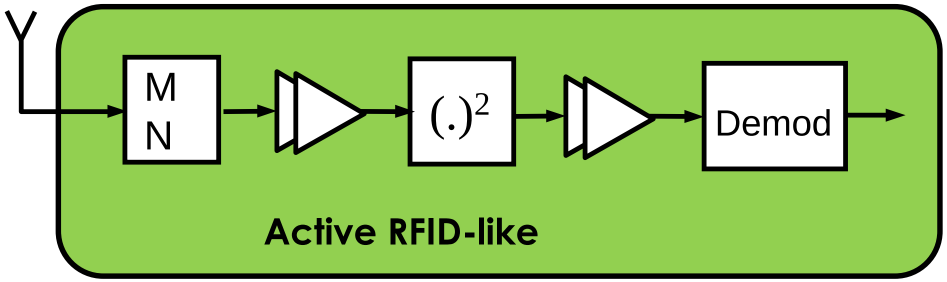
BASIC PRINCIPLE



Ultra Low-Power consumption

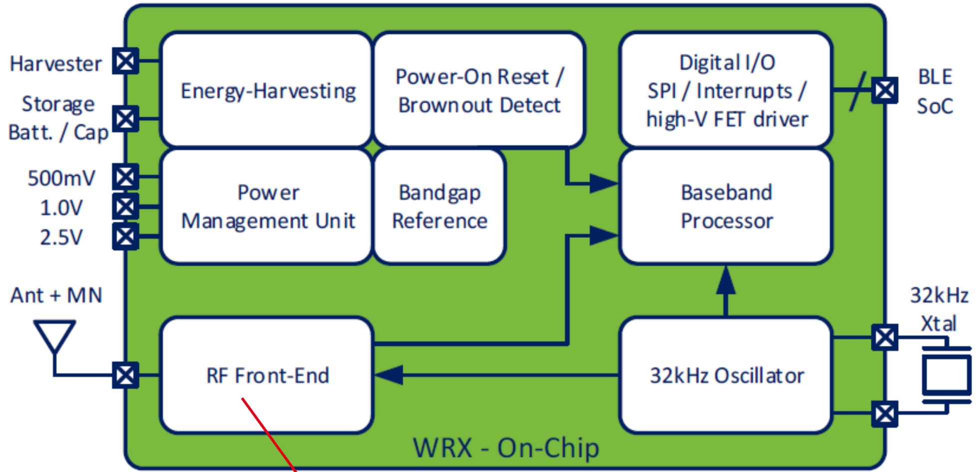
- **No Carrier Synthesis**
  - Fast Start-Up
- **Poor filtering**
  - Large Noise, Poor sensitivity

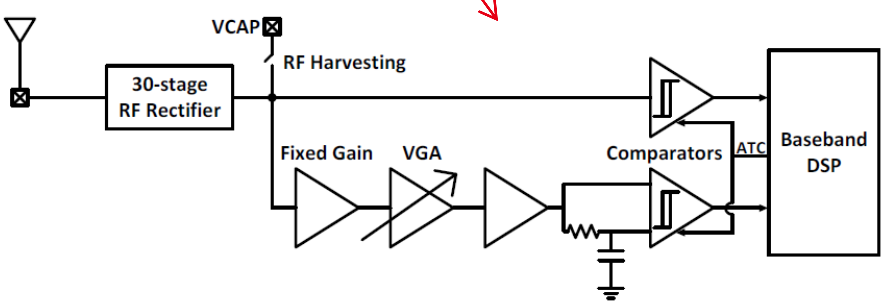
IMPROVED PERFORMANCES



MOST SIGNIFICANT DEVELOPMENT

APPROACH : INSTEAD OF BLE BEACON ADVERTISING TO PHONE, MAKE THE PHONE ADVERTISE TO BEACON





Active Power	580nW
Function	WRX
Integrated PMU	✓
EH Types	PV, TEG, RF
Integrated Tx/Rx	Rx
Rx Sensitivity	-39/-56dBm
Rx Frequency	0.4-2400MHz
Rx Data Rate	8.192kbps
Rx Power	104/236nW
WRX Protocol	BLE/CDMA

MOTIVATION FOR FREQUENCY REFINEMENT

PROS

- Power evolution at constant sensitivity

BW (MHz)	100	40	20	10	5	2
NF (dB)	5,0	9,0	12,0	15,0	18,0	22,0
LNA (mW)	3	1,2	0,6	0,3	0,2	0,1

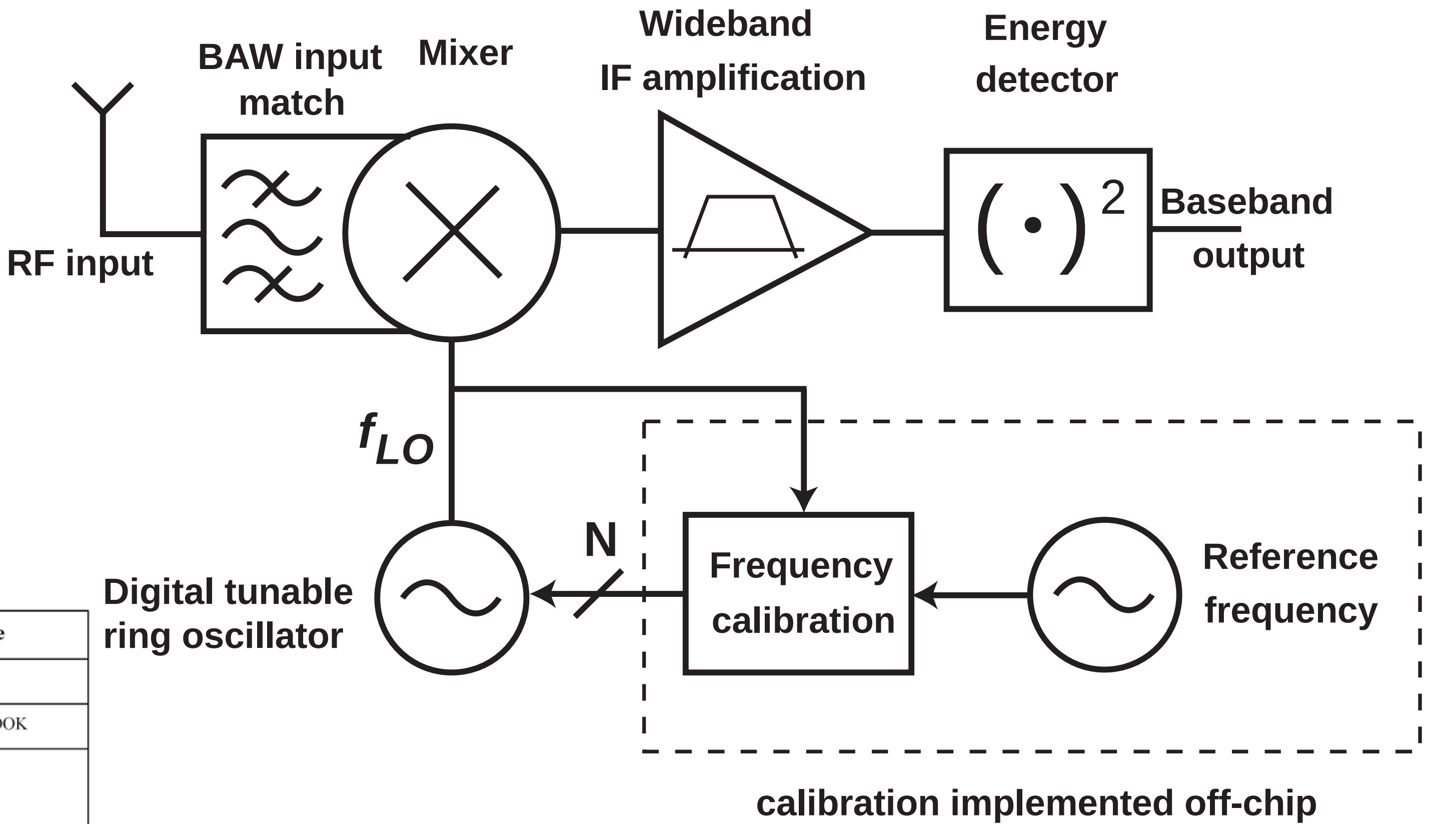
CONS

- Frequency Reference Needed
- Associated Settling Time

FREQUENCY REFINEMENT : STARTING POINT

UNCERTAIN IF

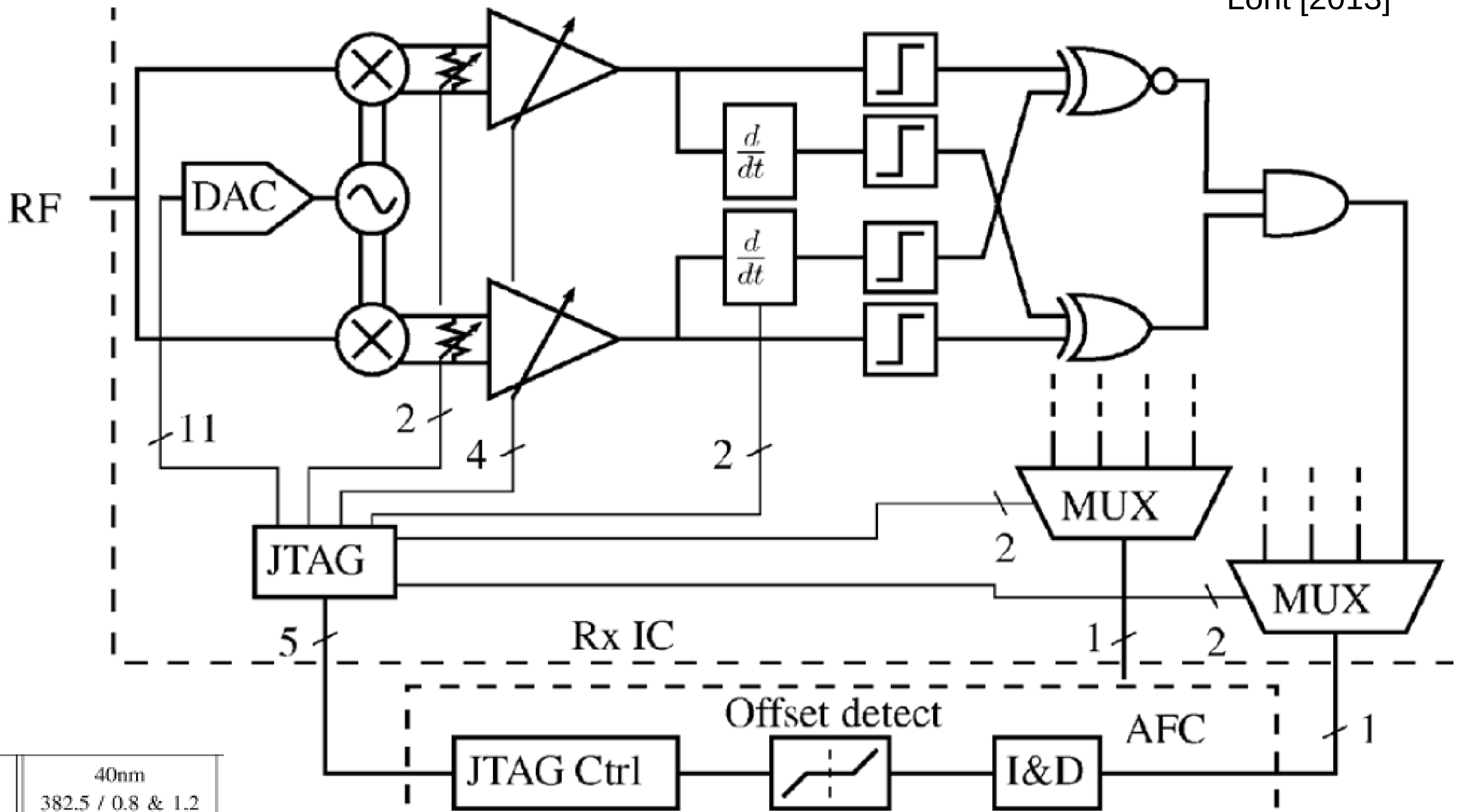
Pletcher [2008]



Parameter	Value
Global supply voltage (V)	0.5
Carrier frequency/modulation	2 GHz / OOK
Power dissipation (μW)	
Mixer	8
IF amplifiers	22
LO + buffers	20
Envelope detector	2
Total	52
Data rate (kbps)	100/200 (nom/max)
Energy per received bit (nJ)	< 0.5
Raw sensitivity for 10^{-3} BER (dBm)	-72/-70 (100/200kpbs)

FREQUENCY REFINEMENT : AFC

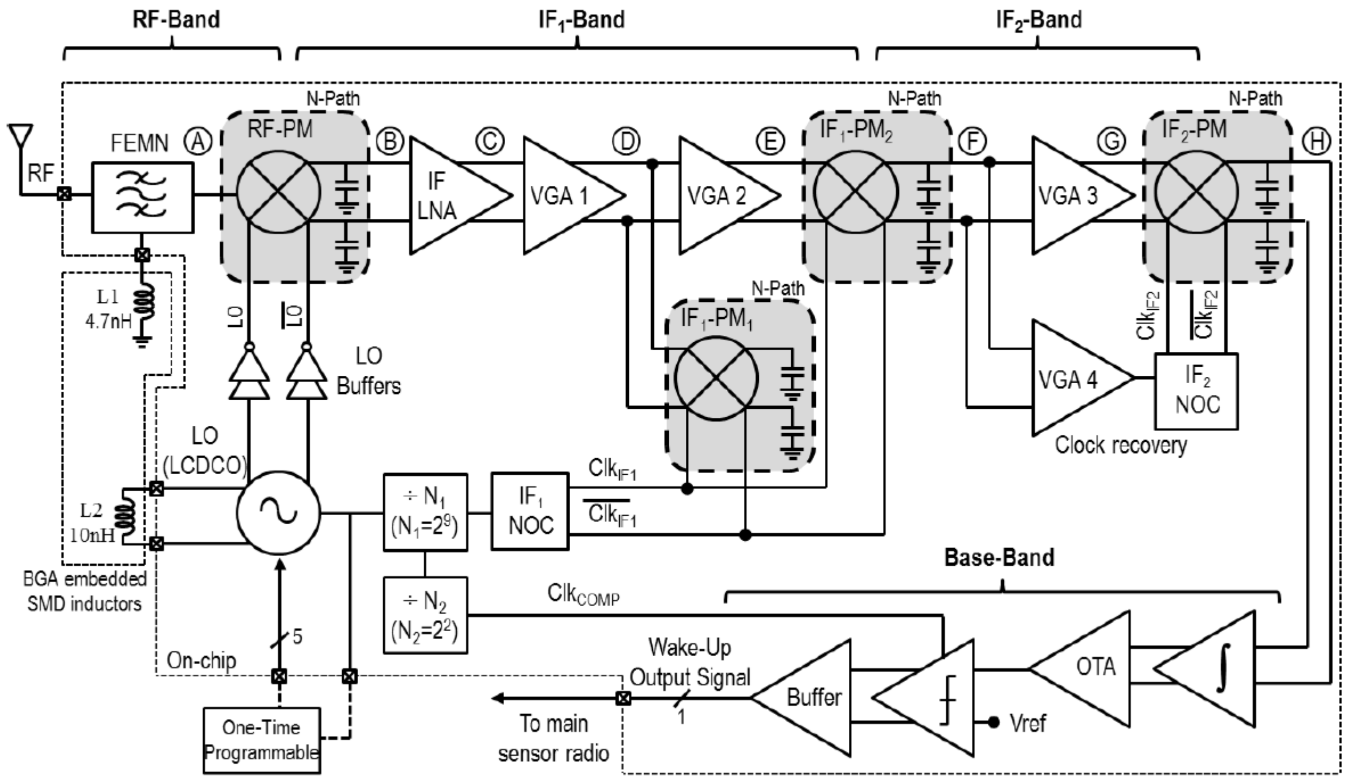
Lont [2013]



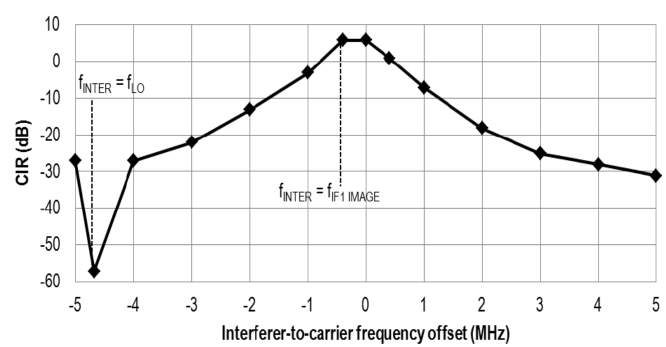
CMOS	40nm
Power (μW / V)	382.5 / 0.8 & 1.2
Freq. (MHz)	782-932
NF (dBm)	11.4
P_{-1dBc} (dBm)	-24
IIP3 (dBm)	-14
P_{sens} (dBm)	-71 (125kbps)
R_b (kbps)	$\leq$625

BLOCKER ROBUSTNESS

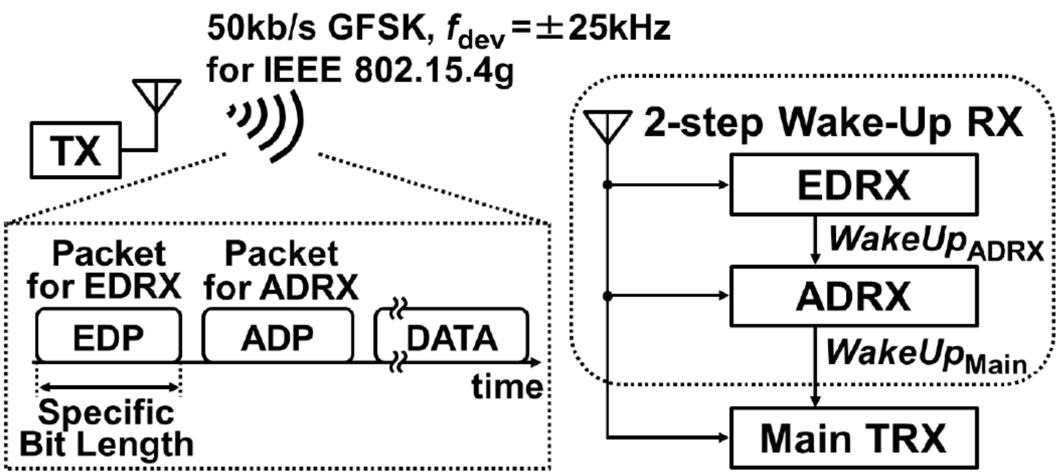
Salazar [2015]

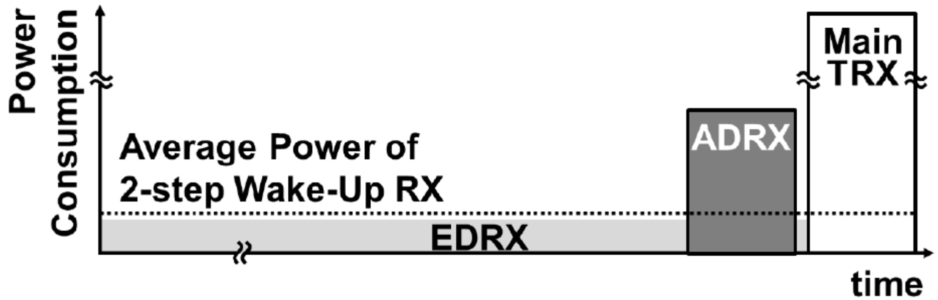


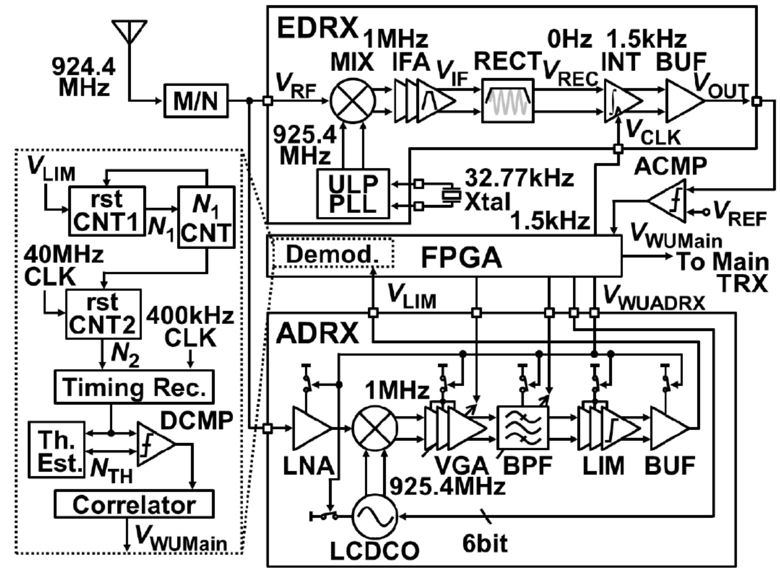
	This Work	
Architecture	Dual-IF	
Interferer filtering technique	Multi-Layer N-Path Filters	
LO generation	Unlocked LC-DCO	
Modulation	OOK	
Power Supply (V)	0.5	
Frequency (GHz)	2.4	
External components	BGA Embedded SMD Inductors	
Duty-cycled	Available	
Power consumption (µW)	99	
Data Rate (kb/s)	10	50
Sensitivity @10^{-3} BER (dBm)	-97	-92
CIR (dB) @ +/-3MHz [%]	-25/-22	
CIR (dB) @ +/-5MHz [%]	-31/-27	



MULTI-LEVEL WAKE-UP







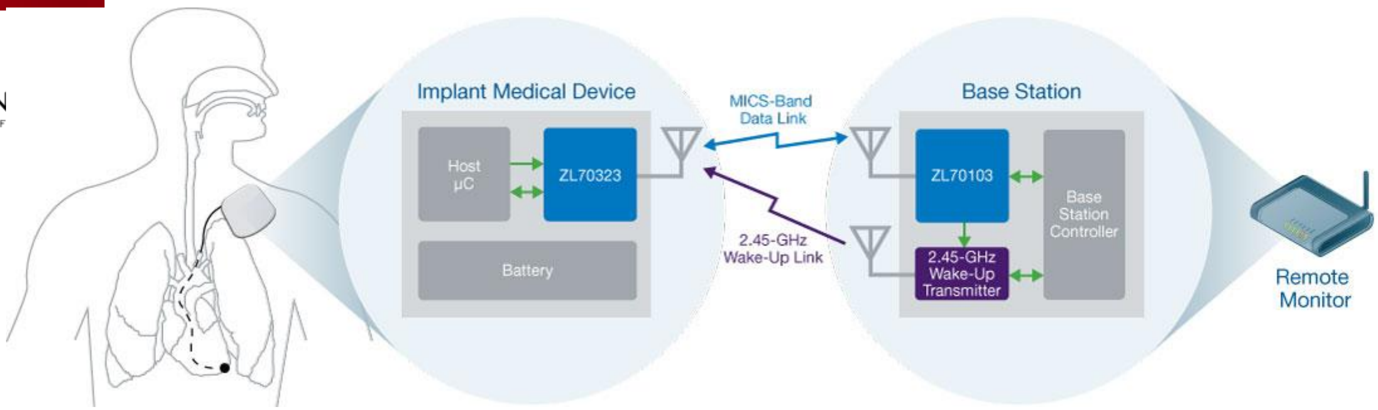
Abe [2014]

EDRX	total:44.2µW
Mixer	0W
ULPPLL	23.8µW
IF Amps	18.1µW
Rectifier	0W
Integrator	2.3µW

ADRX	total:1304.7µW
LNA	531.9µW
Mixer	0W
LCDCO	573.3µW
VGA	47.6µW
BPF	104.3µW
Limiter	47.6µW

Reference	This work
Technology	65nm CMOS
Supply voltage	0.7V
Modulation	GFSK
Frequency deviation	±25kHz
Data rate	50kb/s
Sensitivity	-87dBm
Carrier frequency	924.4MHz
Power consumption	45.5µW※2

INDUSTRIAL EXAMPLE : MEDICAL APPLICATION

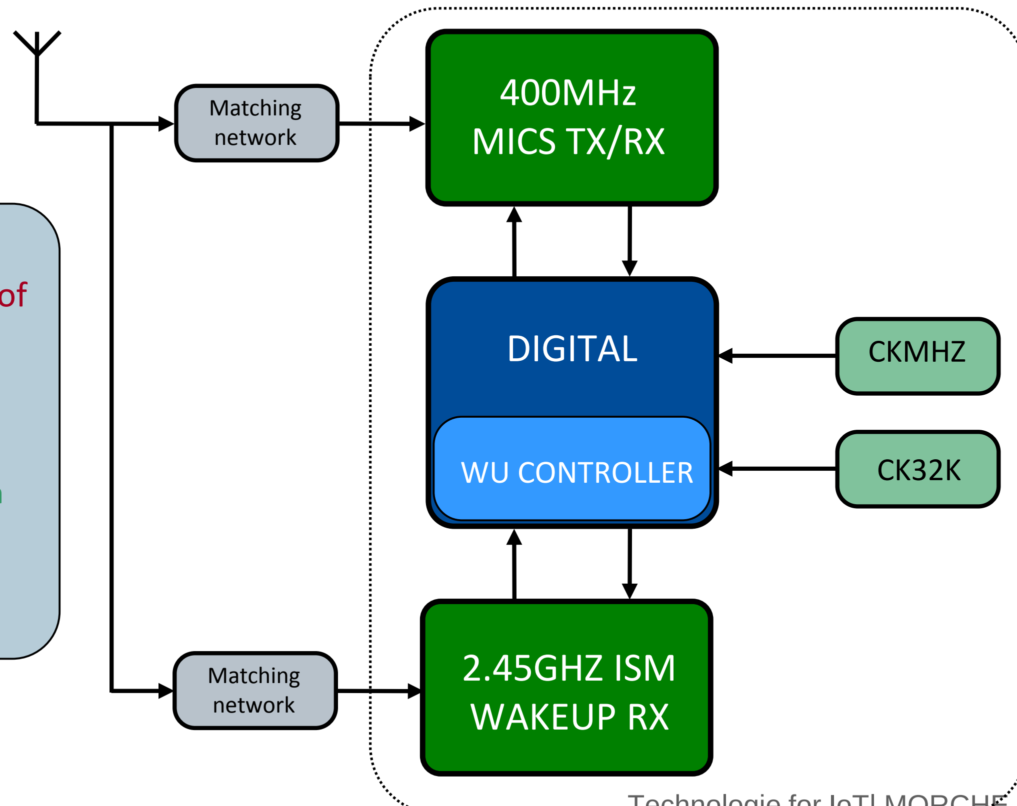


Goal

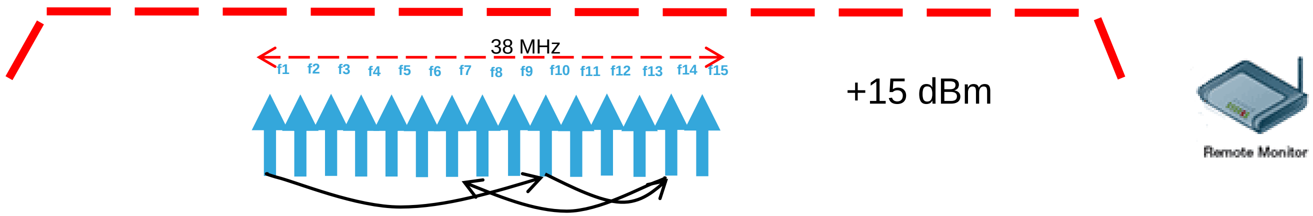
Limit power consumption of the MICS transceiver

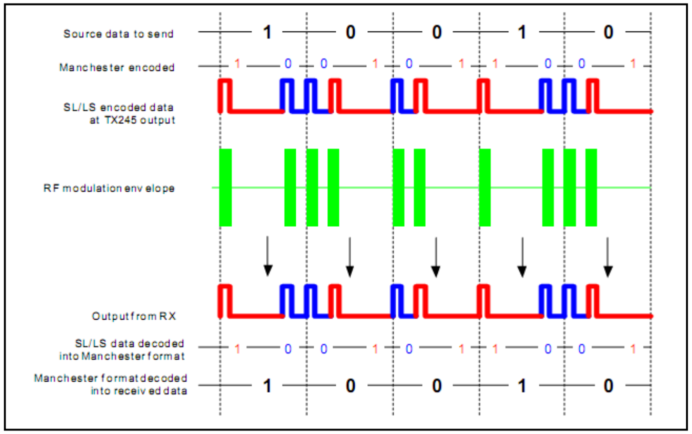
⬇

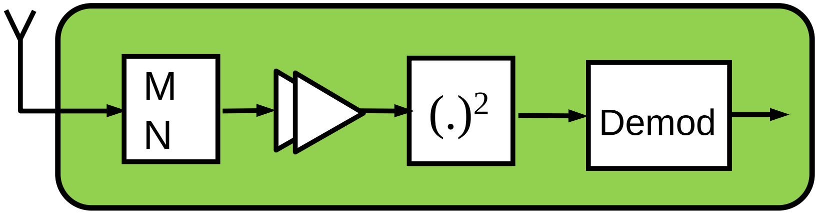
MICS TX/RX is enabled when a right WU frame @2.45GHz is detected



INDUSTRIEL EXAMPLE : MEDICAL APPLICATION







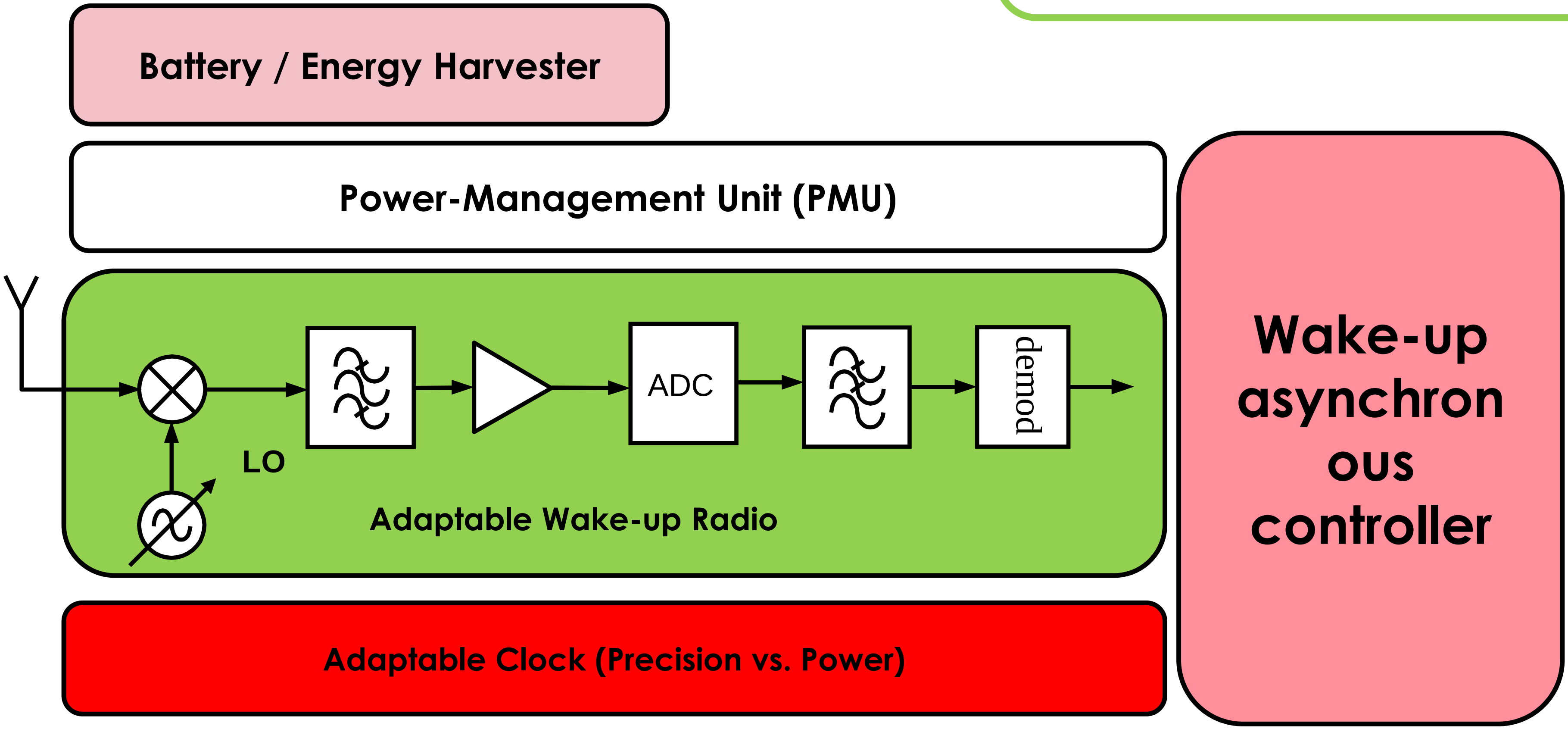
ITEM		VALUES
Sensitivity		-80dBm @ 33kbps
LNA Center frequency		[2.4 – 2.5]GHz
Bandwidth		100MHz
Power consumption	On state	3mA
	Off state	<10nA
	w/ duty cycle 280µs/1s	0.8µW

CONCLUSIONS ON STATE OF THE ART

- Highly active area
  - Lots of publication on that area
  - More and more industrials involved in the area
  - Industrials mostly involved on standardized systems
- High Evolution on the performances
  - With technology evolution and progress in the design
  - Frequency control should be soon mastered
- Wide architecture and performance range
  - Related to the application and to the protocol
- No real cross layer optimisation
  - First publication on wake-up duty cycle in JSSC
  - Lots of potential benefits with this approach

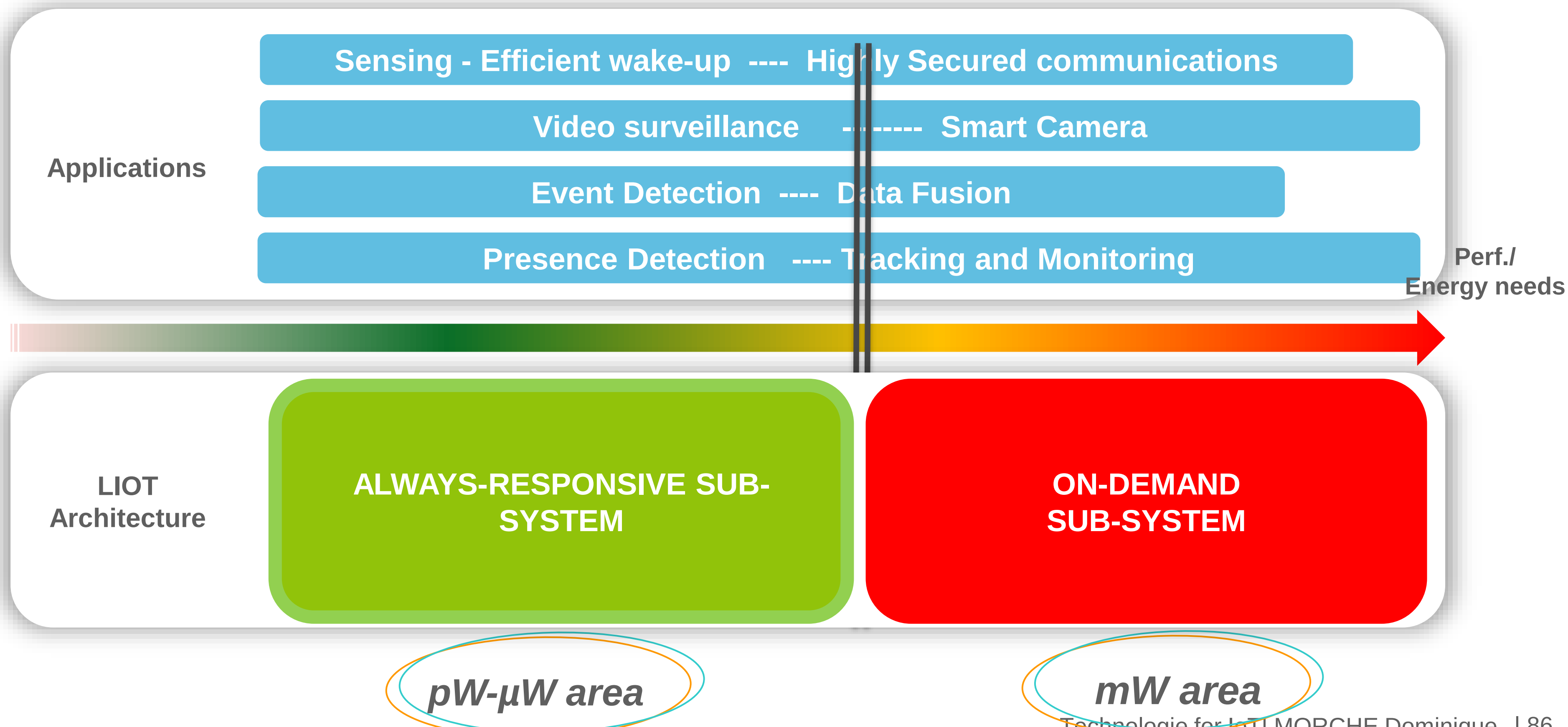
- 28nm FD-SOI
- -65dBm sensitivity
- Less than 50µW
- Compatible with duty Cycle
- -40 dB SIR

WAKE-UP RADIO SYSTEM

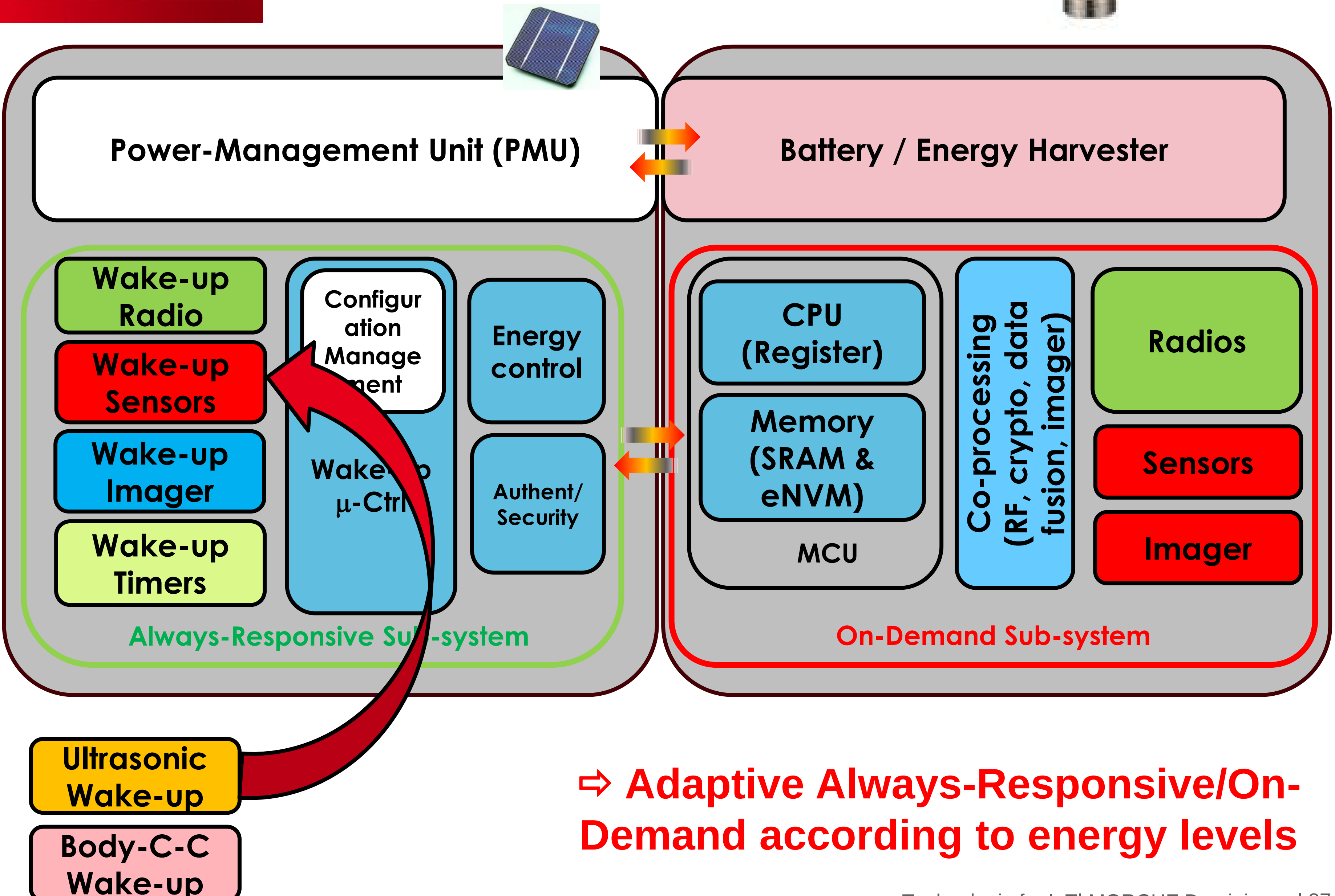


EXTENSION OF THE APPROACH

- A flexible and <u>fully integrated</u> platform for a fragmented market
- FDSOI technology brings more flexibility
- Autonomous system
- Low power consumption and adaptive blocks



L-IOT : A DOUBLE-HEADED PLATFORM

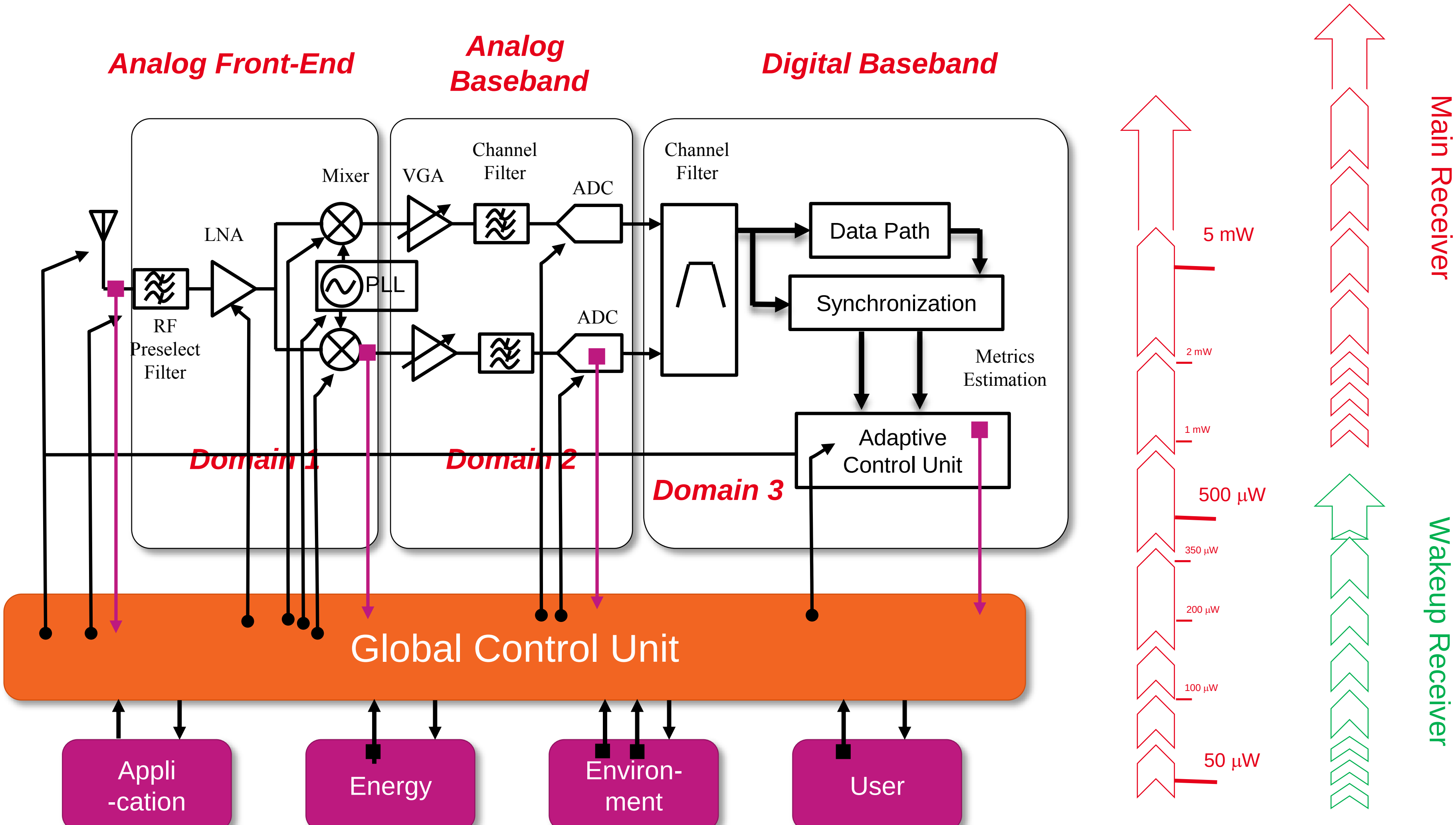


⇨ **Adaptive Always-Responsive/On-Demand according to energy levels**

NEW APPROACH FOR FLEXIBLE RECEIVER

Transceiver Implementation

Flexible Building Blocks



PRESENTATION OUTLINE

1. **Introduction and Prerequisites**

2. **Adaptive Radio**

3. **Wake-Up Radio**

4. **UltraNarrowBand Approach**
   - SigFox Network
   - Slides from C. Fourtet, SigFox CTO

IOT AND M2M CONNECTION : WHICH NETWORK ?

	Pros	Cons
Cellular : GPRS, 3G.. Optimized 4G in few years	Large Networks exist	Cost, Consumption ! (terminal must be disciplined)
PMR : Mobitex, Terta, specific	Large Networks exist, Reliable	High Cost. Dedicated to profesionnal
ISM : Proprietary, Mash, ZigBee	Low Cost	Not scalable
Satellite	Large coverage	Relatively high cost. Not Flexible

KEY FACTS ABOUT AVAILABLE SPECTRUM

- **Cellular spectrum is and will always be expensive**
- **Private Spectrum as well**
- **ISM Spectrum is not large and drastically limited and constraints (power, duty cycle)**
- **TV White space are no global, if not just a « Mirage »**
- **Potential future specific allocation for M2M will take a long time, as ever (10 years)**

You should better get organized for a maximum optimization

KEY GOALS FOR TOMORROW'S M2M/IOT

- Low Cost …. And even ultra low cost
- Ultra low current drain
- Consequence of above : keep devices as « low talker » or listener as possible, and avoid to « discipline » them through complex protocol
- However : Need for high scalability… tens of billion of objects
- Keep CAPEX and this infrastructure as low cost as possible at start-up
- Plan to standardize
- Many things to be reinvented compared to classical networks

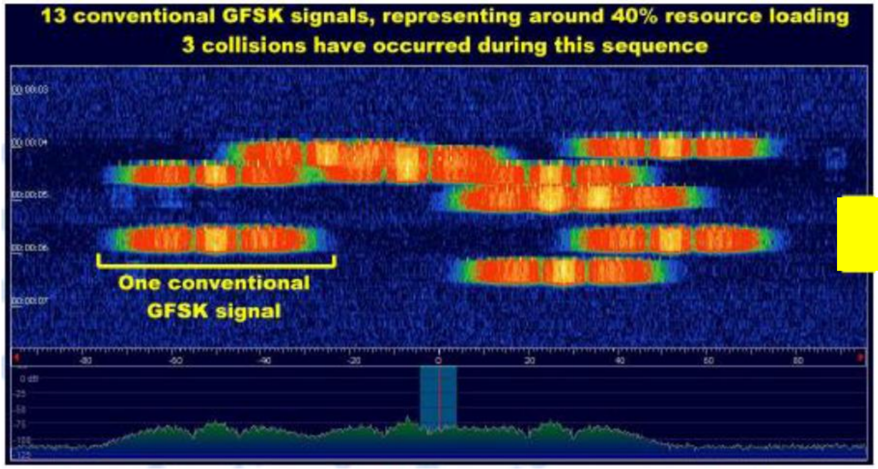
THE PARADOXES

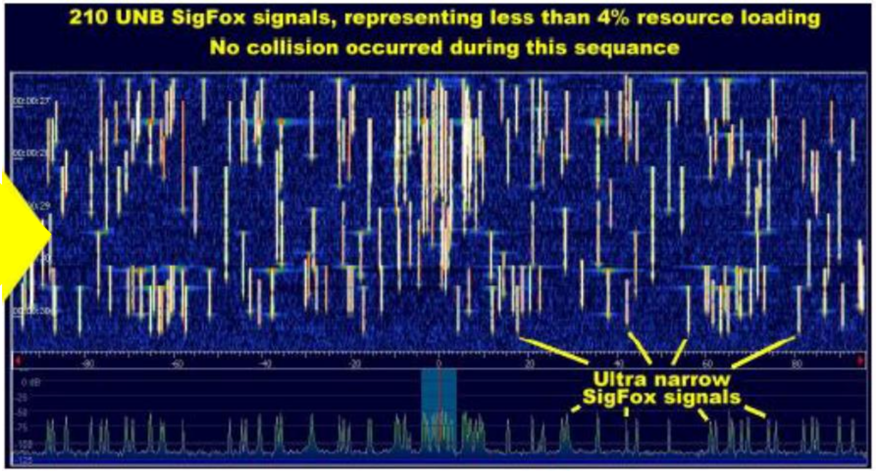
- You need large cells for minimum CAPEX, thus long ranges
- But you want low power
- And despite large cells, you still want scalability on tiny spectrums, thus very high capacity per MHz
- However…devices are not disciplined for low consumption and low complexity/cost

It seems you need to put intelligence in the network and use advanced techniques like Cognitive SDR

NETWORK COST : WHY ULTRA NARROWBAND

- **How to optimize your available spectrum ?**



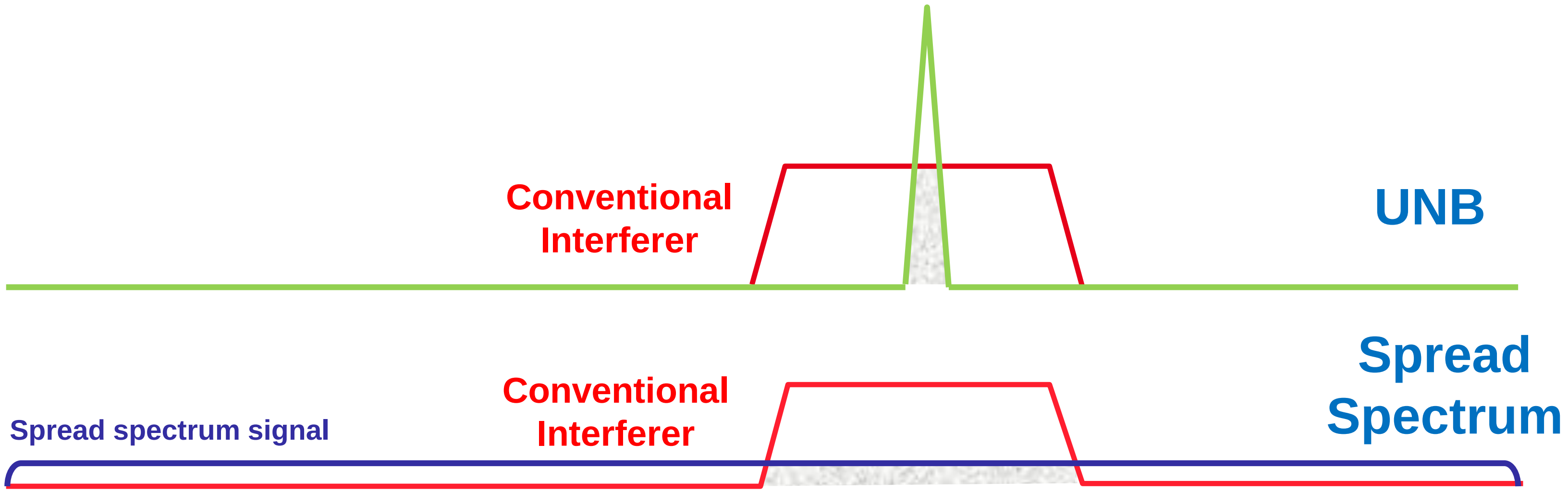


But Narrowband techniques have been almost abandoned for more than 40 years. Why ?

Because the more you work narrowband, the more tuning is complex, the more stability issues are of first importance… and thus the more expansive are your systems ! But Sigfox has find a solution to circumvent this issue

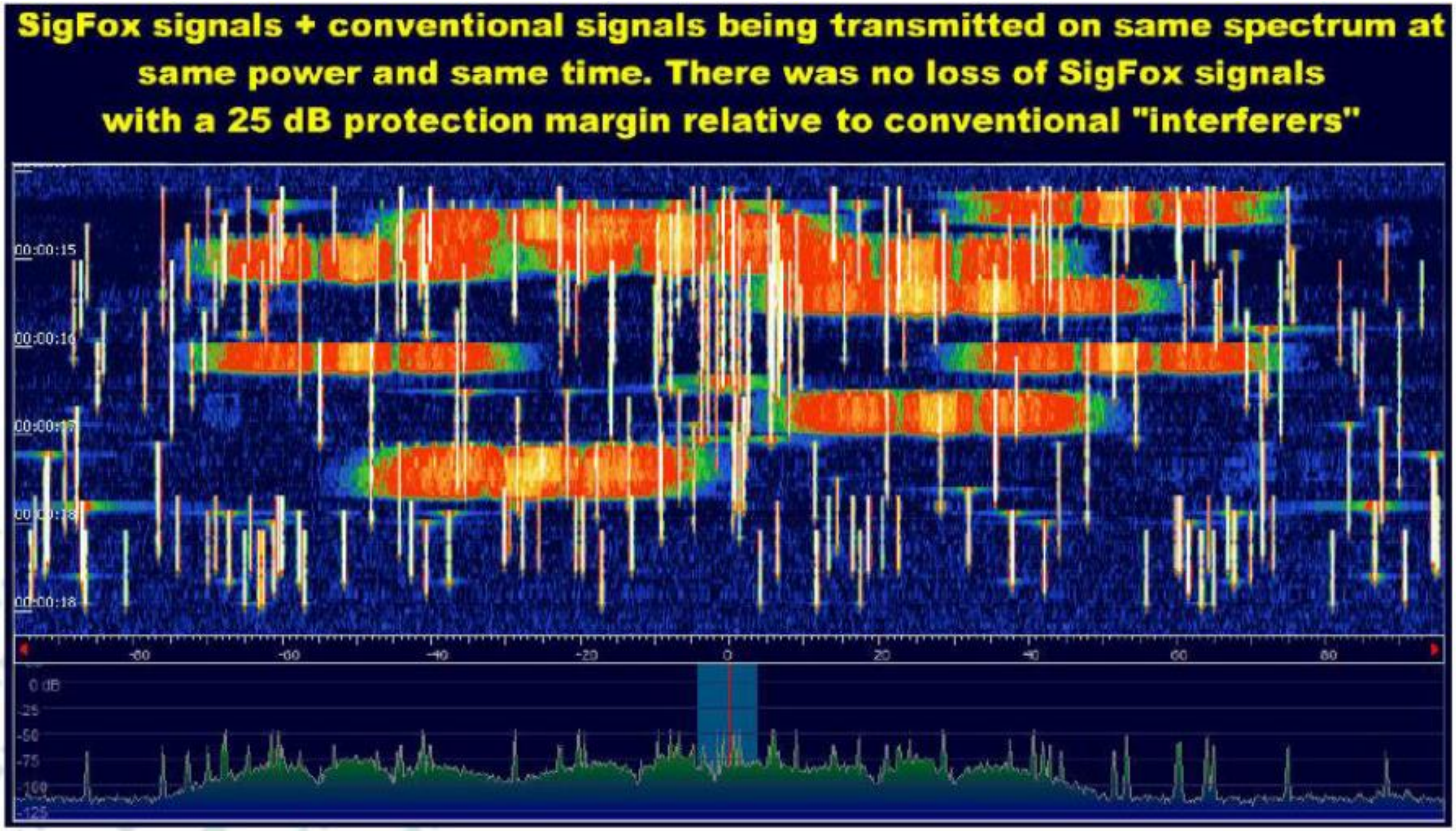
BUT THEN, WHY NO OVER TECHNIQUE

- **Spread Spectrum is another option without stability issues**
  - Good technique for blocker robustness



- **However, if the tuning issue is solved, UNB might be superior**
  - Simplicity of terminals
  - SS requires disciplining terminals for spreading code attribution
  - Better capacity, the narrower you operate, the higher is the capacity
  - The narrower you operate, the lighter is the protocol
  - No frequency/channel management. Terminals are free running

VALIDATION OF THE APPROACH



Typically up to 3 Million devices per day on a single BS for 3 transactions per device per day and only 8% spectrum loading

HOW ARE SOLVED THE UNB ISSUES

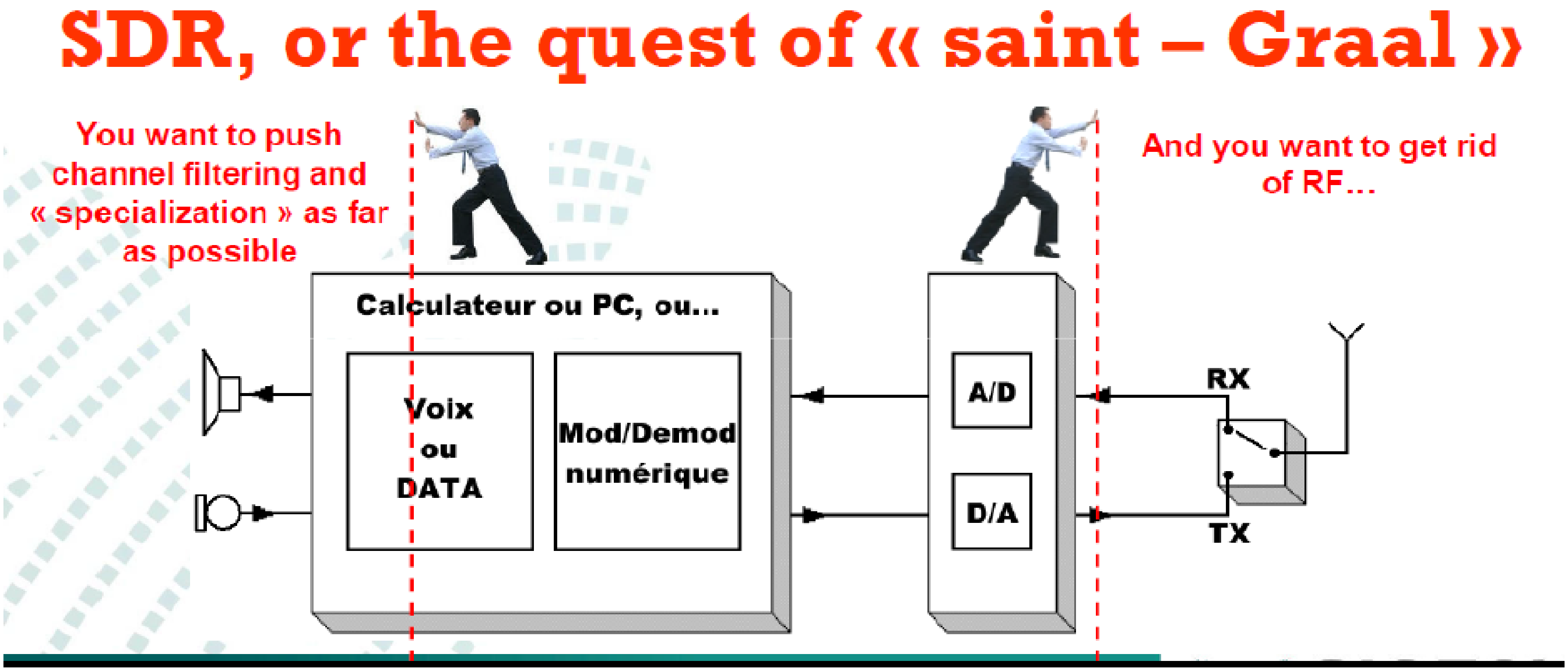
- Do not care about terminals « imperfections », like static or dynamic stability, among others. Put effort on station's SDR software that will compensate for it !
- Highly multisession thanks to software to handle thousands of simultaneous signals
- High dynamic range BS radio (120 dB)

And what about UNB Issues in Terminal ?

- Uplink is extremely simplified. Almost whatever commercial chip can be used. Dynamic frequency instability are corrected in the BS. Terminal is free to impose its frequency hopping
- Bidirectional terminal's receivers do not need BS sophistication because, one again, network compensates for their weaknesses. You can operate UNB without stability concern

SDR IN FEW WORDS

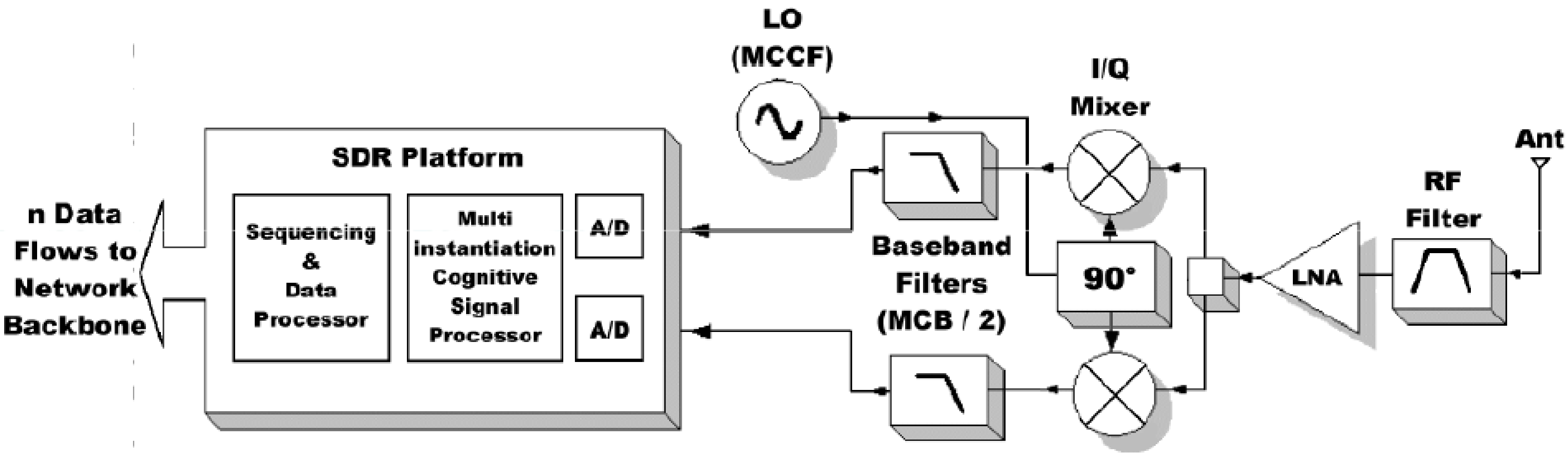
- SDR concept appears in the 80's, first prototypes developed by US labs and companies like Raytheon, Thomson, Rockwell
- J.Mitola was the first in 1991 to introduce terms of « SDR » as well as « Cognitive »
- First 70Msamp/s digital IF cellular base station introduces on the market around 2000
- Today : mobile phone



A COGNITIVE MULTI-INSTANTATION SDR

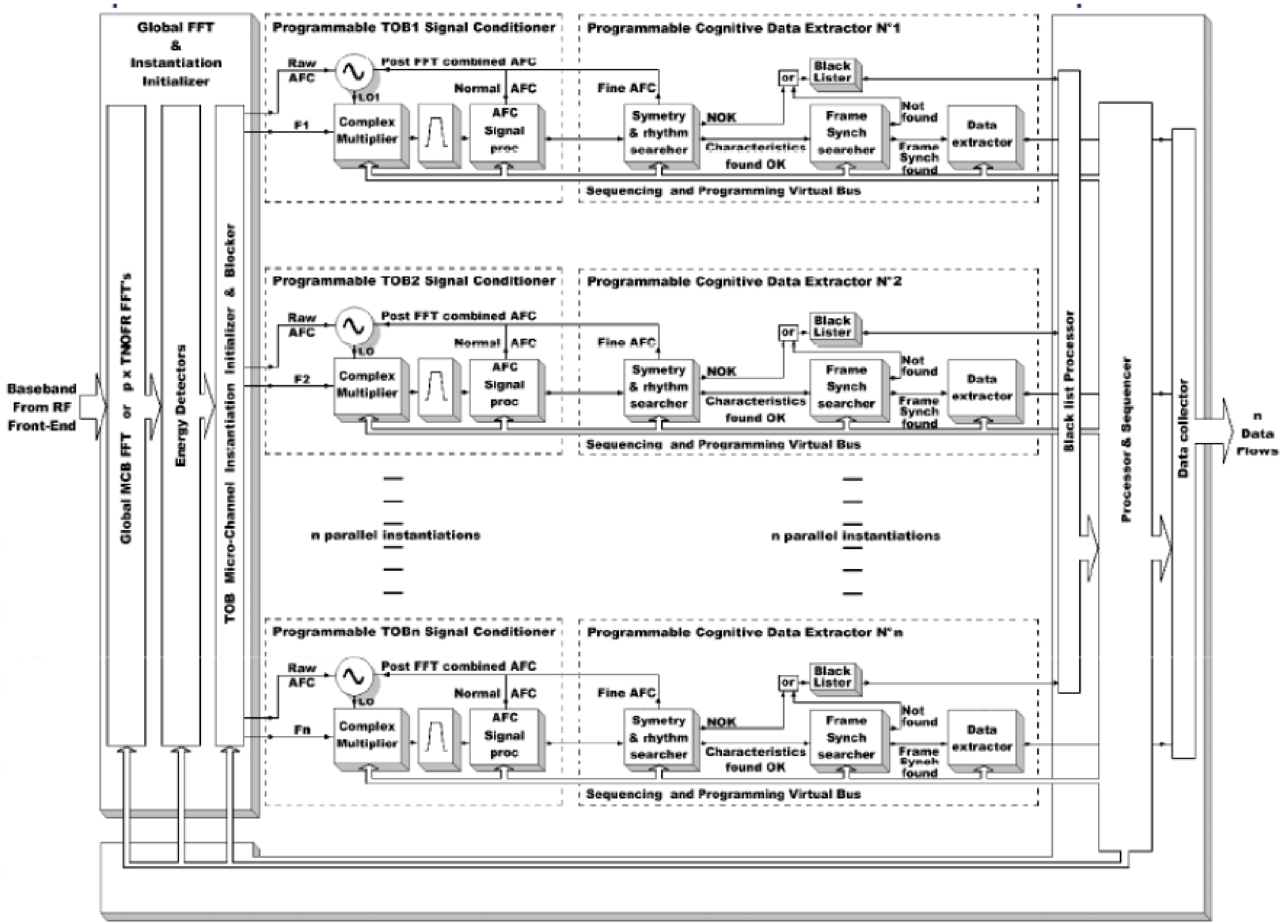
- A common RF and A/D for multiple software instantiations, each of them dynamically « discovering », identifying and demodulating a specific UNB signal among a plurality of others -> One RF = N receivers

- Same principle for transmission : compute a complex multi-signal (multi-carrier), sent to a unique D/A & RF



A COGNITIVE MULTI-INSTANTIATION SDR

- An example of a multi-branch demodulator : Software implementation

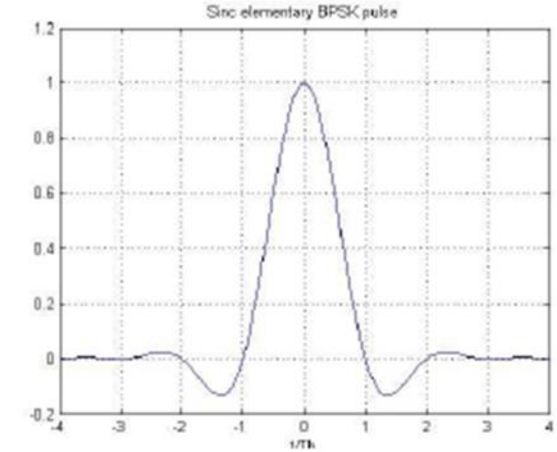


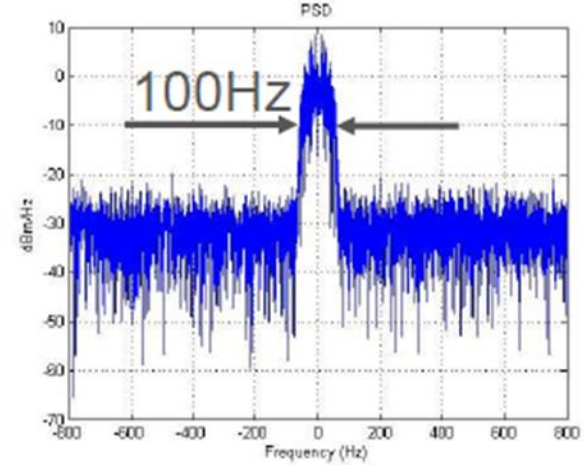
LPWAN radio characteristics – SIGFOX UNB

- Uplink:
  - DBPSK modulation @ 100 bps
  - Frequency: 868.13MHz +/- 100kHz
  - Link budget = +14dBm (Tx) – (-145dBm) (ntw sensitivity) = 159dB >> GPRS
  - 12-byte payload per message
  - Message duration = 3x2s
    - Repeated 3 times on 3 random frequencies within band
  - Energy spent per message Etx = 3 x 2s x 50mA = 300mAs = 83µAh

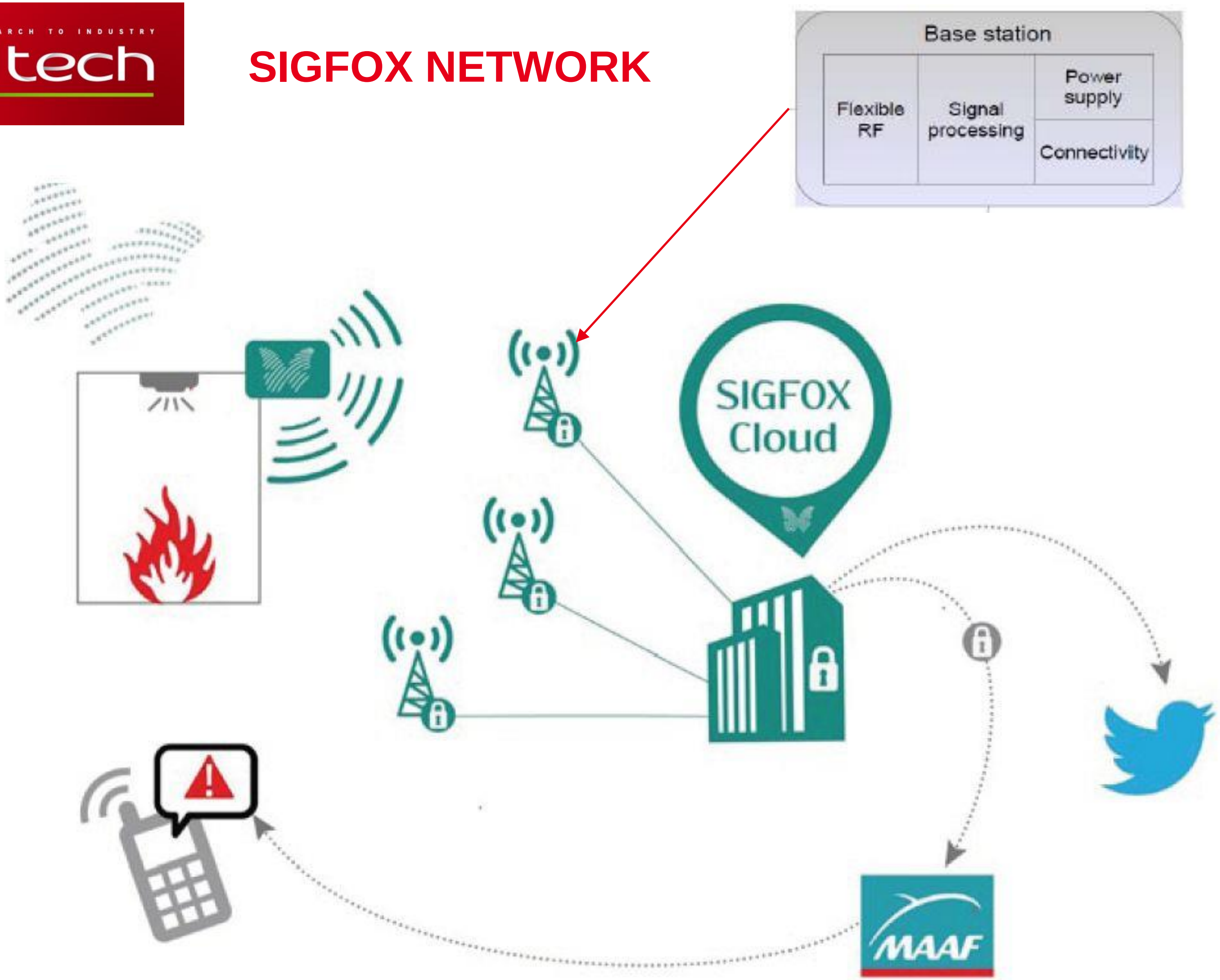
- Downlink:
  - FSK modulation @ 500 bps
  - Frequency: Uplink + 1.4MHz (869.5MHz +27dBm sub-band)
  - Link budget = +27dBm (Tx) – (-126dBm) (node sensitivity) = 154dB >> GPRS
  - 8-byte payload per message
  - Message duration = 300ms with average latency of 10s
  - Energy spent per message Erx = 10.3s x 15mA = 154mAs = 43µAh

- As sensitive as GPS wrt frequency stability!

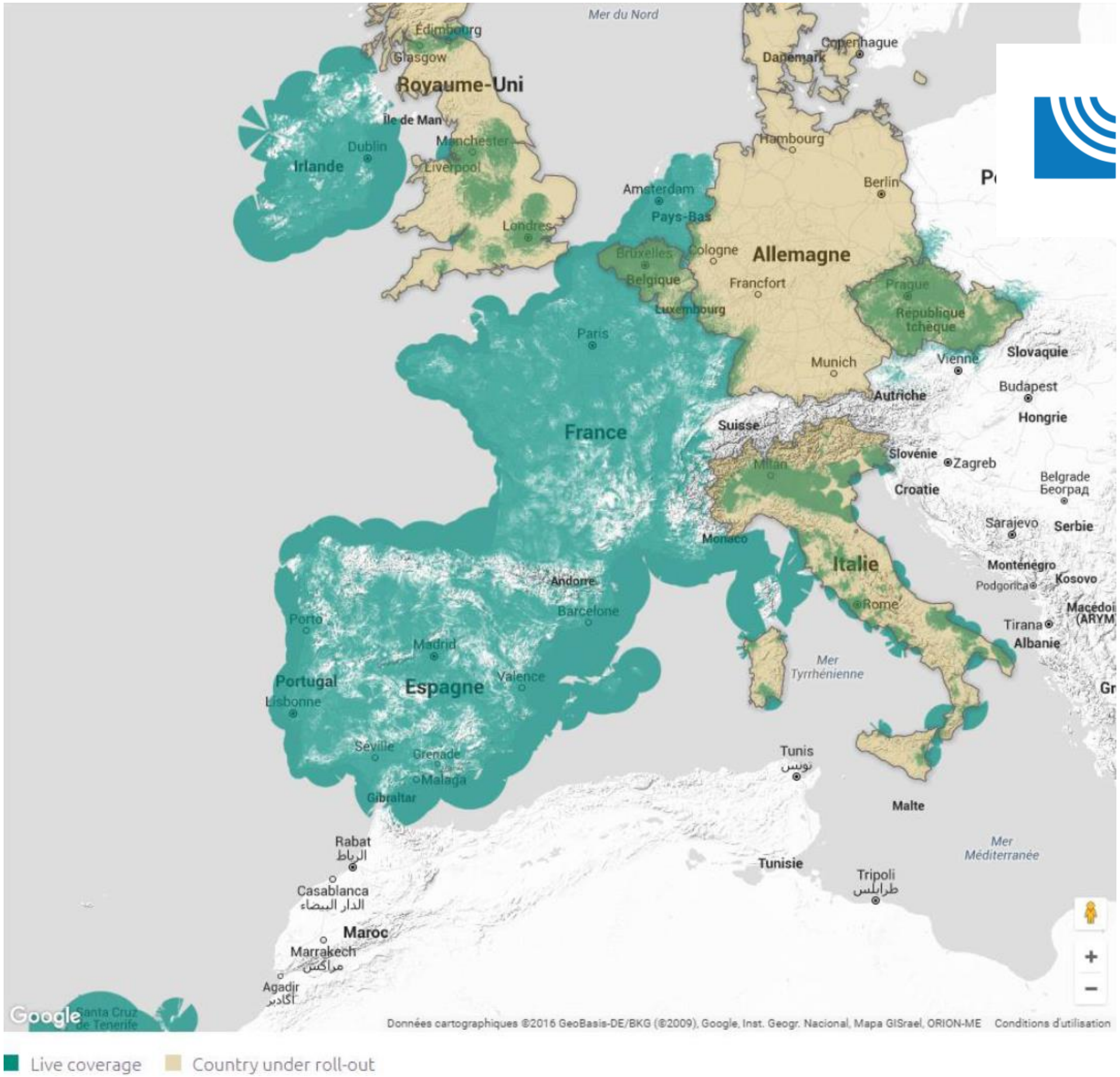




SIGFOX NETWORK



TODAY'S COVERAGE



from 1 to 9 Euros per months

12 octets of data

From 0 to 140 messages per day

from 50 to 100 μW per bit instead of 5000μW in cellular

COVERED APPLICATIONS

"Preparing for take-off: scaling the LPWA opportunity using NB-IoT", Luke Ibbetson, Vodafone, June 2016

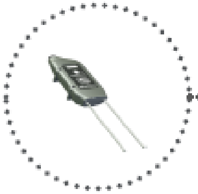
What Opportunities does NB-IoT Enable?

Gas metering
Large homogenous market measured in millions
Battery life and propogation is critical
Large number of potential meter manufacturers

Water metering
Large homogenous market measured in millions
Battery life and propagation is critical
Large number of potential meter manufacturers

Liquid and pressurised fuels
Large homogenous market measured in millions
Asset is currently un monitored & losses are high
Battery life and propagation is critical

Smart Bins
Growing market with good business case
Battery life and network coverage is critical
Complements our hi end connected bins



Environmental Monitoring
Latent market waiting for a low power solution
Battery life and network coverage is critical
Fragmented channel to market in low volumes

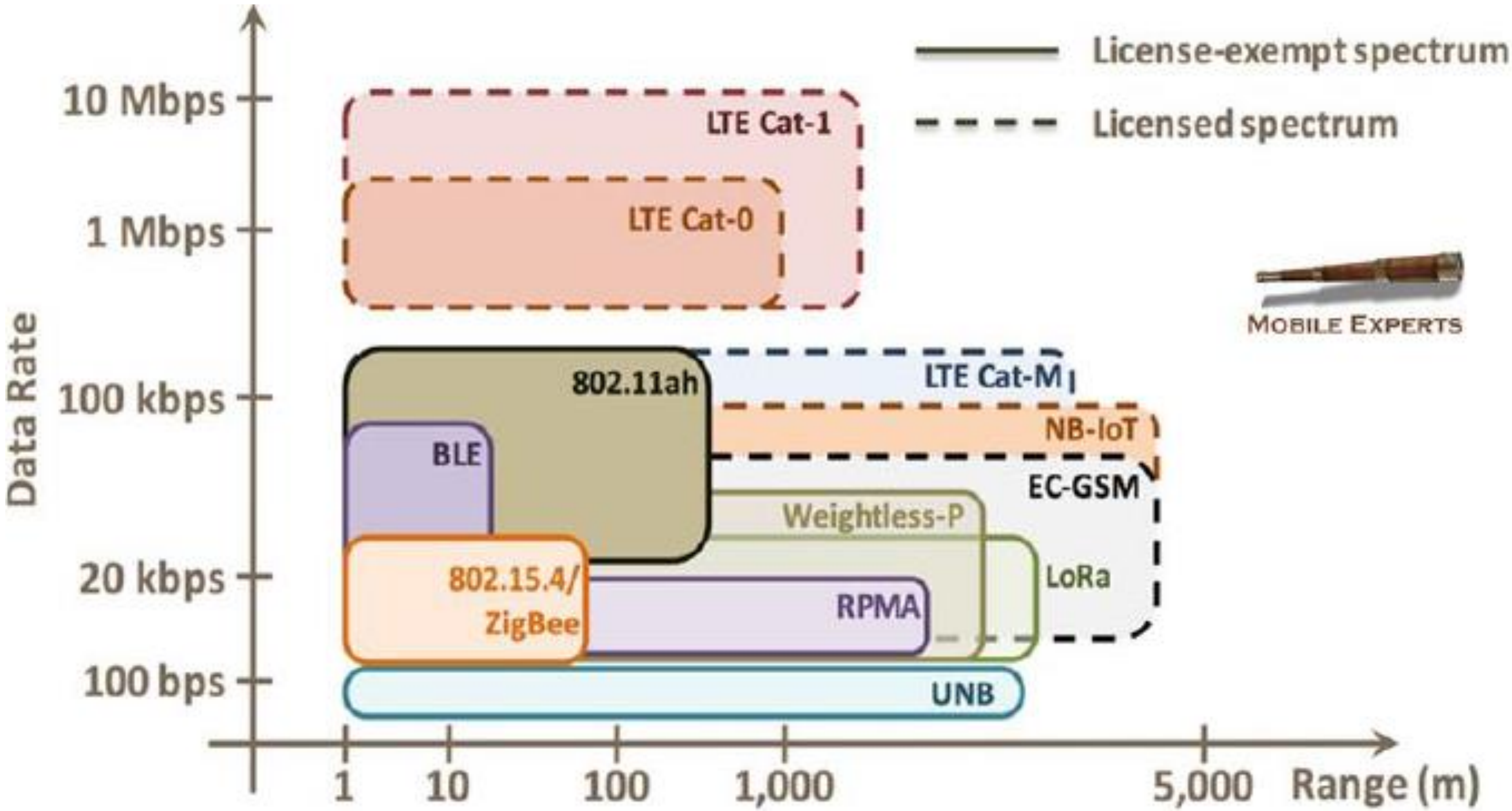
Smoke and fire alarms
Massive market measured in hundreds of millions
Battery life and ability to test device is critical
High volume B2C play

Parking monitoring
Market measured in hundreds of thousands
Battery life and low install cost are critical
Low data throughput

Alarms and event detectors
Market measured in hundreds of thousands
Battery life is ultra critical
Very low data throughput on check and trigger

LPWA IN AN IOT LANDSCAPE

« LPWA vs LTE Introduction », Madden, Mobile Experts, LPWA, June 2016



CONCLUSION ON UNB

- **THE EVOLUTION :**
  - Classical Radio is always connected
  - Wake-Up Radio is listening with a poor quality
  - UNB is never listening the channel…

- **LPWA IS A VERY INTERESTING OPPORTUNITIES**

- **LOTS OF POSSIBILITIES**
  - Licenced vs unlicensed
    - More Services with the operator
  - UNB vs Spread Spectrum
    - More flexibility

- **LPWA will not cover the whole iot market**

CONCLUSIONS ON IOT

- **High Disillusion**
  - Two Many expectations on this highly demanding market
  - Two may start-up on the same topics
  - Technical challenges
  - Rapidly evolving data market

- **High Potential**
  - 2/3 of the most important company are not existing today

- **More probability to gain on the services area**

- **But more benefit and margin by joint optimization between services, network and hardware…**

THANKS

FOR

YOUR

ATTENTION

Commissariat à l'énergie atomique et aux énergies alternatives
17 rue des Martyrs | 38054 Grenoble Cedex
www.cea-tech.fr

PRESENTATION OUTLINE

- **Introduction and Prerequisites**
  - Market & Forecast
  - Buzz World or Reality
  - Radio Issues

- **Adaptive Radio**
  - Motivation
  - Basic Approach
  - Limitations

- **Wake-Up Radio**
  - Different Approaches
  - Existing Architecture & Solution
  - Extension of the concept

- **UltraNarrowBand Approach**
  - SigFox Network