Cyber-Physical Systems for Aeronautic Applications

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Cyber Physical systems

- Krogh et al., 2008 :
  - Cyber-Physical Systems: integration of physical systems with networked computing

- Wireless sensor networks are expected to be an important infrastructure for gathering and exchange physical information

Outline

- Objectives and specifications of cyber-physical systems for aeronautic applications

- Proposed solutions
  - Network architectures
  - Physical layer : digital base band, RF front end, frequency choice, smart antenna and integration – SoC approach
  - MAC layer and synchronization
  - Wireless Sensor Network simulator for aeronautic applications taking into account our hardware solutions

Long term objectives for aeronautic systems

- **Eco-efficiency**
  - Greener systems
  - Lowest carbon emissions
  - Less weight
  - Higher performance
  - Cost efficiency
  - Passenger comfort
  - Global system challenge → global system solution

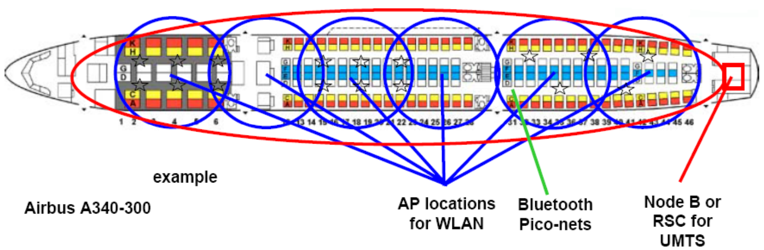
- **Time to market**

Target applications for cyber-physical systems

- Flight test instrumentation
- Pilot – crew communications
- Structure Health Monitoring
- In-flight tests
- In flight Entertainment – Wireless Cabin

Target applications for cyber-physical systems

- Wireless flight test instrumentation
  - Long term research
  - Weight problem → eco-efficency → green systems → wireless
  - Set-up the system: sensors, communication, power
  - Safety and security – major problems
- Wireless pilot – crew communications
- Wireless In flight Entertainment – Wireless Cabin
  - Audio et video transmissions
  - Internet on board
  - Easy reconfigurability of the cabin



Structure Health Monitoring

Hard landing problem

- Goals: Reduce aircraft schedule interrupts by:
  - Reducing number of false reporting hard landings
  - Aiding the maintenance process

- Current process
  - Pilot initiate inspection
  - Large number of false reports
- Process with structure health monitoring
  - Pilot initiate inspection
  - Flight parameters and structure health monitoring sensor information will be used to predict load information in critical structure areas
  - Recommended maintenance action
  - Aid maintenance process

Structure health monitoring benefits

- Reduce maintenance effort
- Increase aircraft availability

- Component history record
- Predictive diagnosis

- Wired : weight problem and time deployment problem
- Green systems : wireless

- Independent instrumentation

SHM system requirements

- Low or medium data rate, low power nodes
- High number of nodes, different kind of sensors
- Synchronization measurements
- Able to connect to aircraft network (AFDX or Ethernet)
- No interferences with passenger equipment

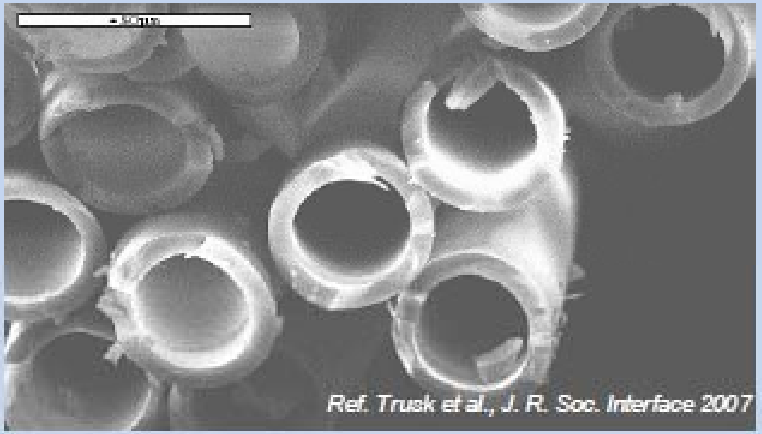
- Difficulty to use COTS :
  - Medium numbers of nodes
  - Not Deterministic
  - Without Synchronization
  - Interferences with passenger equip…

Rethinking the entire hardware – software system
hardware reconfigurable solution

Far future

- In the far future – smart materials, composite materials → self –healing !

Vascular system for healing resin in sandwich structures



Self-healing ability in visionary aerospace composites is able to reduce the inspection efforts and provide rapid repair

Aeronautic In Flight Tests Application

Aeronautic in flight tests objectives

- Needs to dispose data describing the behavior of aircraft before commercialization
- Decrease the weight
- Decrease the cost of the system (cables)
- Decrease the cost and the complexity of the system deploying

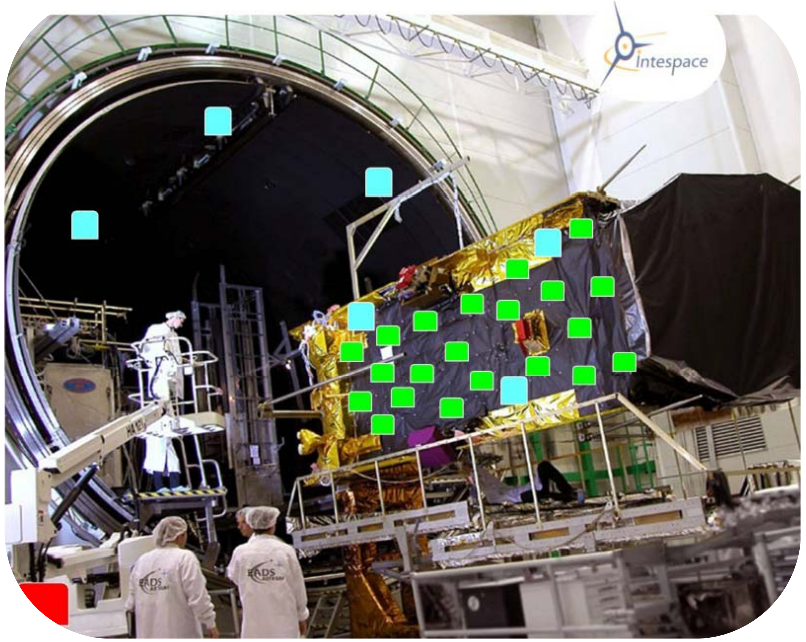
- The wireless cyber-physical system will replace the existing test equipments whose sensors are still connected by wires
- **Wireless communications solve many problem for the end user but induce strong innovative developments**

In flight tests

- Real time measurement of the wings pressure profile
- Real time description of the behavior of mechanical structure
- Verifying and validating results of virtual wind tunnels model

Satellite ground test applications

- Real time description of the behavior of mechanical structure such as satellites during dynamic tests.
- Gather the structure deformation at different points where strain gauges and accelerometers are implemented



ICONS 2010 – J.Henaut, D.Dragomirescu and al, "Validation of the MB-OFDM Modulation for High Data Rate WSN for Satellite Ground Testing"

In flight tests –challenges of the system (1/2)

- High number of points of measure
- Frequently updating of the measure

→ High data rate

- No data loss can be tolerated (low BER requested)

↓

- Strong channel coding and efficient transmission in harsh environment

- No power sources on the wing

↓

- Low power nodes

- Gathering data in real time to a central PC in the plane connected to the Ethernet/AFDX bus

In flight tests –challenges of the system (2/2)

- No interference with critical systems ➡ Very low radiating power: UWB

- Precise identification of each sensor
- Precise synchronization of the all sensor measures

⬇

- Deterministic MAC layer with synchronization algorithm

ICN2010: T. Beluch, D. Dragomirescu et al. "Cross-layered Synchronization Protocol for Wireless Sensor Networks"

Laboratoire d'Analyse et d'Architecture des Systèmes

In-flight Test System Requirements

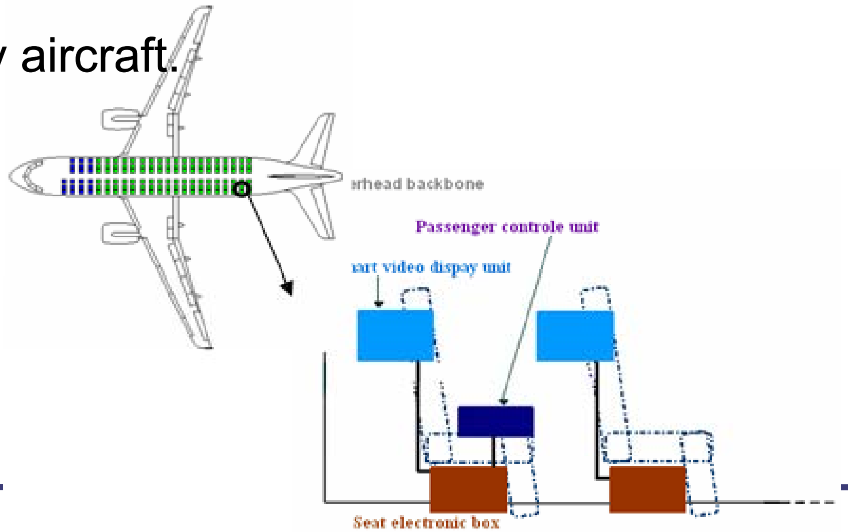
- System requirements :
  - Low power nodes, High number of nodes, High data rate
  - Real-time
  - Measurements synchronization for all the sensors
  - Connected to the cabin to a central PC
- Impossible to reuse COTS:
  - Low and medium data rate
  - Not real-time systems,
  - Medium numbers of nodes
  - Not Deterministic
  - Without Synchronization

- Rethinking the entire hardware – software system
- hardware reconfigurable solution

In flight Entertainment
Wireless Cabin

IFE system - the constraints

- Technologies authorized in major countries
- Wireless system has to prove it works as well as the wired one (ex : reliability)
- Reduce onboard system weight, size, power…
- Use only standardized devices (and COTS if available)
- Keep passengers comfortable
- Financial efficiency = 12 h flight by day by aircraft.



Wireless IFE Requirements

- Constraints
  - 300 users
  - Canal indoor (Office LOS)
  - Ah hoc network self organizing (using localizatio
  - 50 cm between seat rows, 70 cm large seat
  - Frequency >5 GHz
  - Smart antenna
  - Expected throughput ~1Mbit/s at least
- Wireless COTS solutions cannot b yed in an aircraft
- Problems of frequency, availability a efficiency with such a number of nodes in such a small area - aircraft passenger cabin

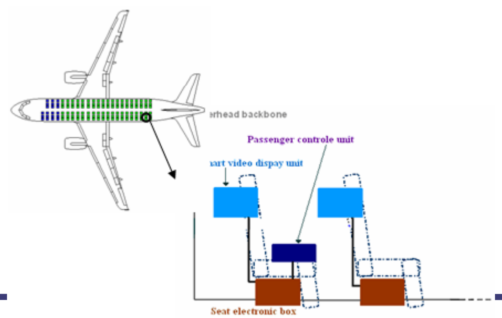
Rethinking the entire hardware – software system

- hardware reconfigurable solution

Cyber-physical Aeronautic Systems requirements

Cyber-physical Aeronautic Systems requirements

- Low cost, low power, small size, simplicity, high number of nodes
- Application dependent constraints
    - Data rate
    - Radio range
    - BER
    - Spectrum occupation



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Proposed solutions

- Active Wireless Sensors Networks → cyber-physical systems
  - Gathering physical information
  - Application specific hardware → reconfigurability (physical layer and antenna)
  - New Services are needed
    - **Synchronization**
    - **Time stamp**
    - **Localization**
    - **Safety, security**
  - Cross-layering between low network levels (PHY and MAC) and high network levels (routing)

Research fields

- Physical layer: SoC
  - IR-UWB
  - MB-OFDM (see our papers at ICONS 2009 and 2010)
  - 6 - 8,5 GHz and 60 GHz band
  - CMOS IC design
  - Smart antenna
    - Beam-forming using phase shifter
- MAC layer and synchronization
- Simulator for WSN
  - Network topology
  - MAC layer
- Cross-layering
  - Take benefit of the highly reconfigurability of lower layers to the high layers
  - uP integration – routing, SoC approach
- Focus on **flexible substrate integration**

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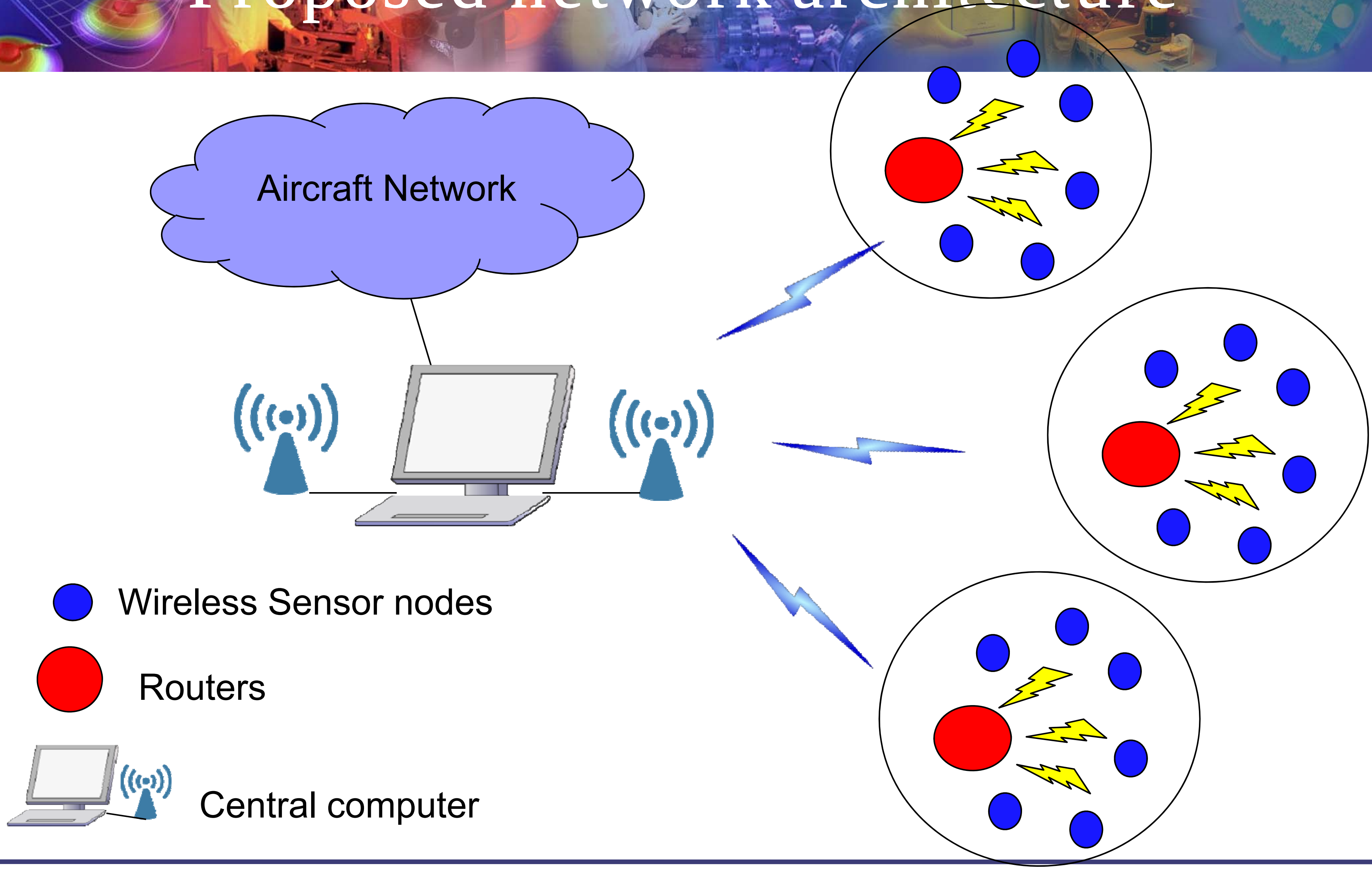
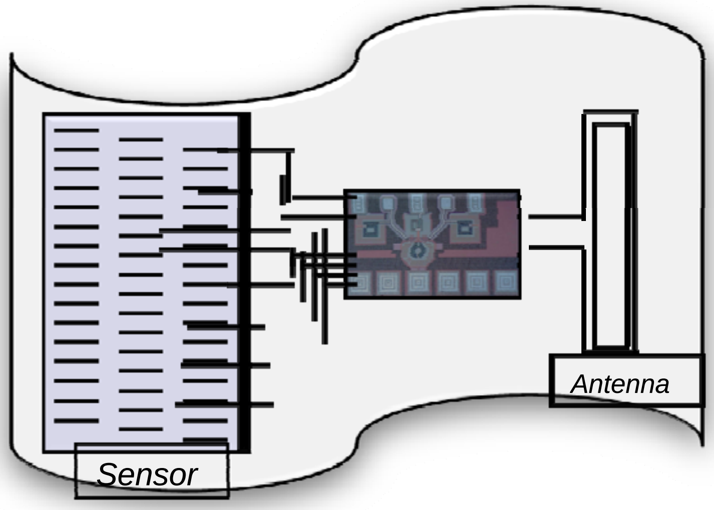
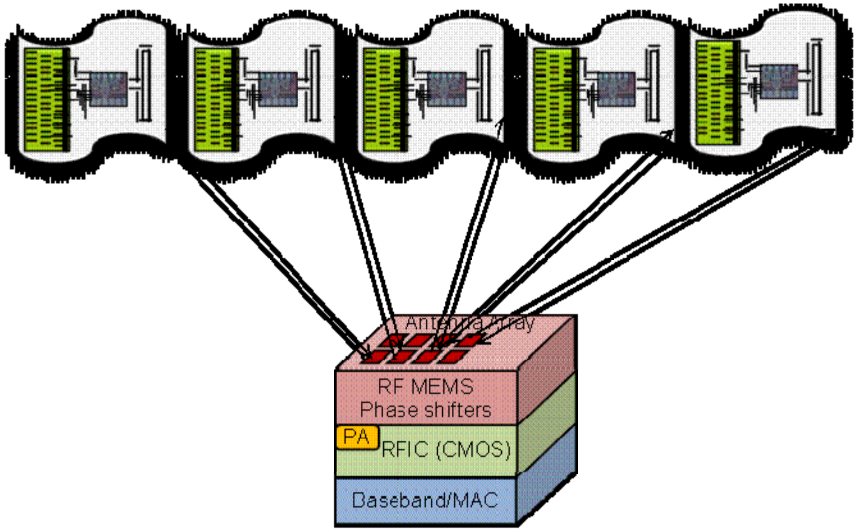
Proposed network architecture



Network architecture

- Flexible substrate architecture for the nodes
  - Low power transceiver integrated on flexible substrate together with the sensor and the antenna
- 3D integration with smart antenna for the routers, for example, in SHM applications





ANR NanoInnov – NanoComm Project

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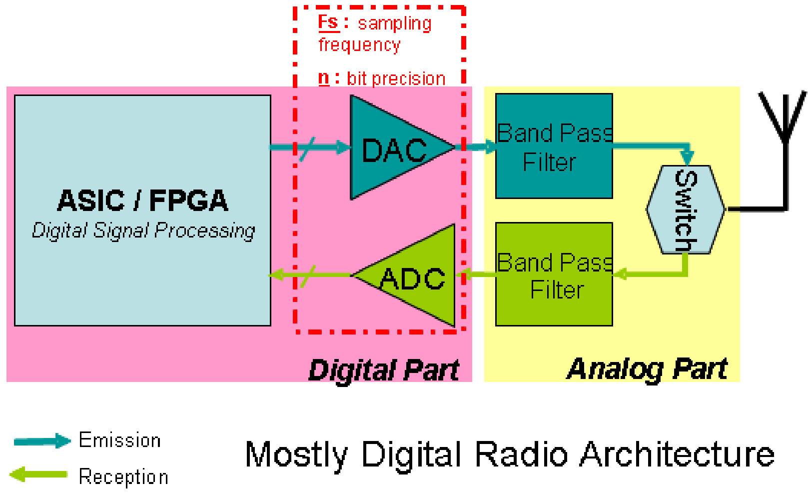
The advantages of UWB-IR

- Low level discontinue transmission
  - Low power transmission
  - Large frequency band
  - Very short pulse
  - Lower interference probability
  - Fine temporary resolution
    - Localization

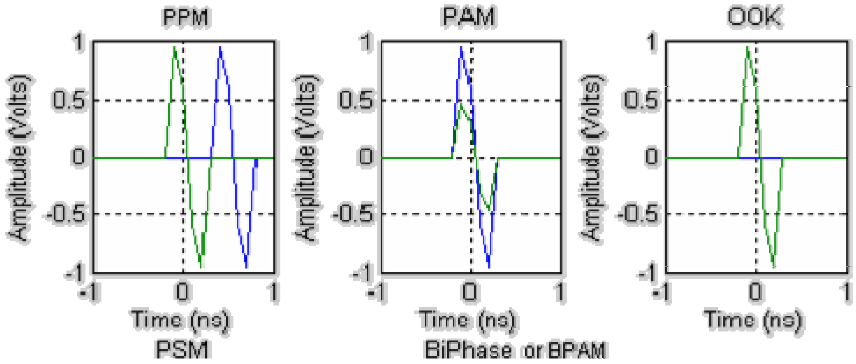


Mostly Digital Radio Architecture

- Low complexity circuits to be developed in CMOS technology → low cost, low power
- Challenges :
  - Channel estimation
  - Fast DAC/ADC
  - Reception synchronization

IR-UWB

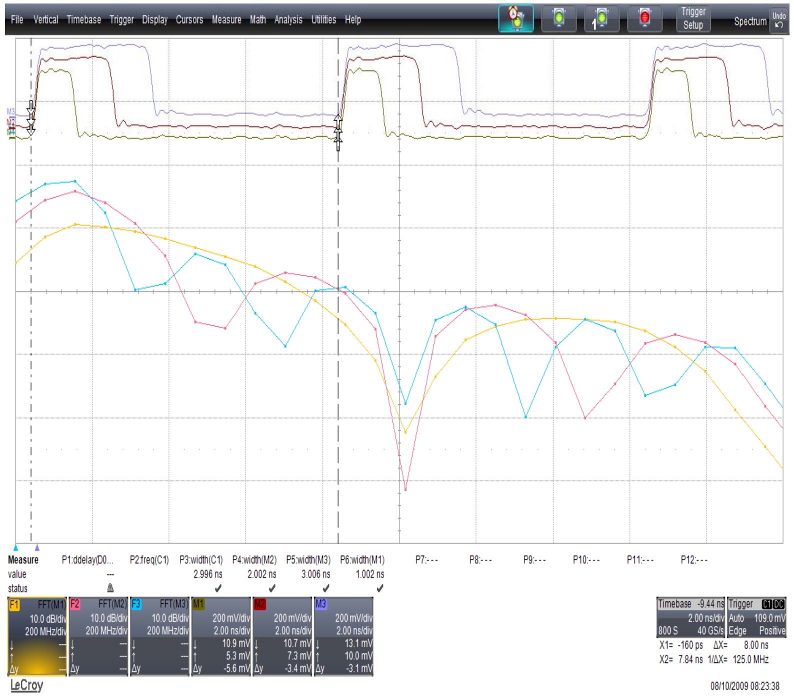
- IR-UWB



- Emitter – receiver architecture
  - Mostly Digital architecture → high reconfigurability
  - Mixed architecture : digital – analog RF front end → 60GHz
- High data rate →
  - channel capacity → directive antenna and 60GHz
  - transceiver architecture
- BER
- MAC layer for IR-UWB

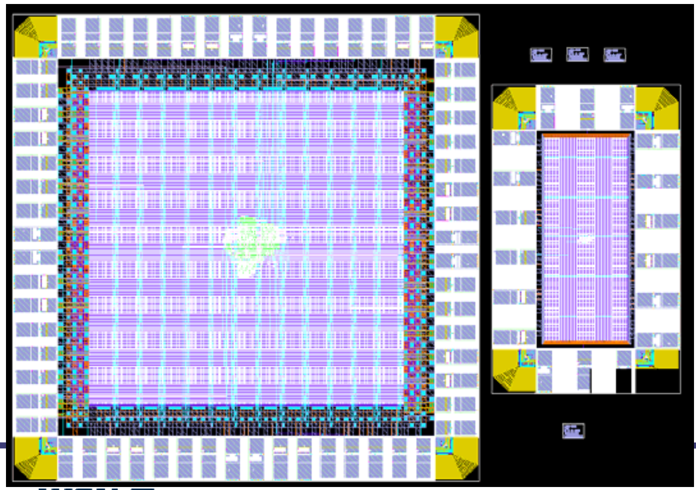
FPGA prototypes

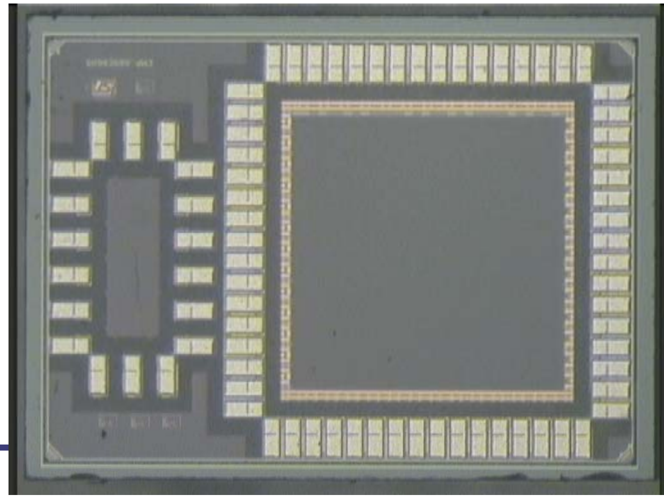
- IR-UWB multi user emitter and receiver
- IR-UWB receiver with localization function
- IR-UWB reconfigurable transceiver in modulation, pulse duration, spectral occupation, data rate and user code
- IR-UWB reconfigurable transceiver at 120Mb/s – state of art: 50Mb/s (Electronics Letters, March 2010)



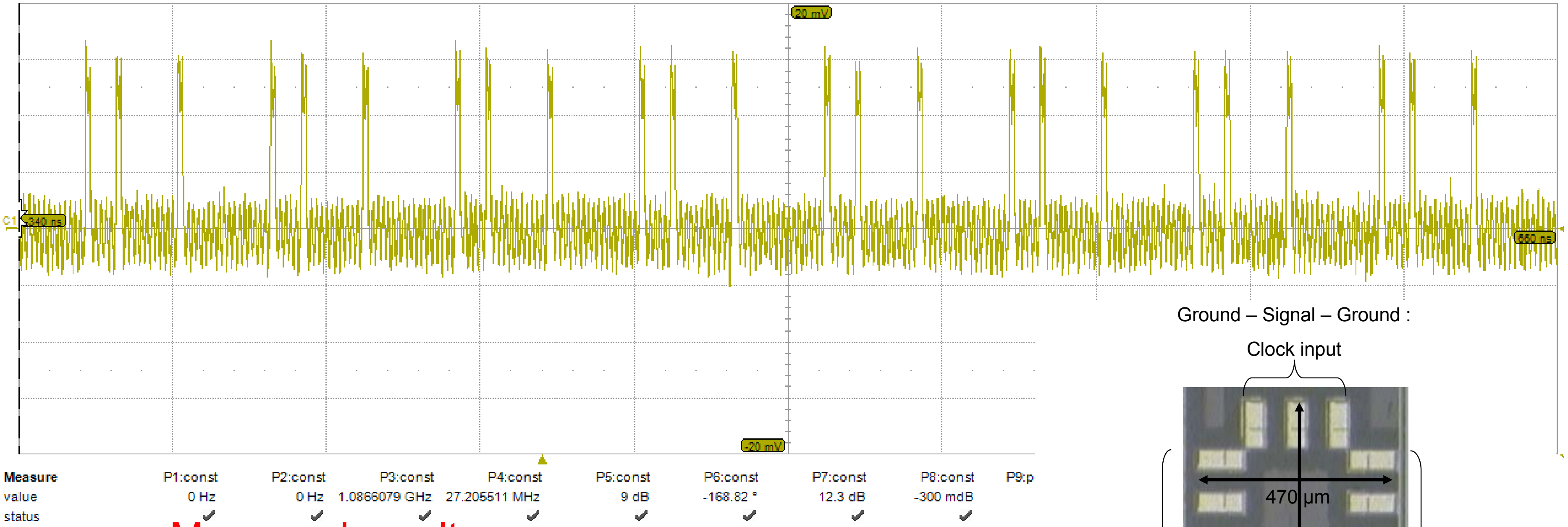
ASICs - emitter UWB-IR

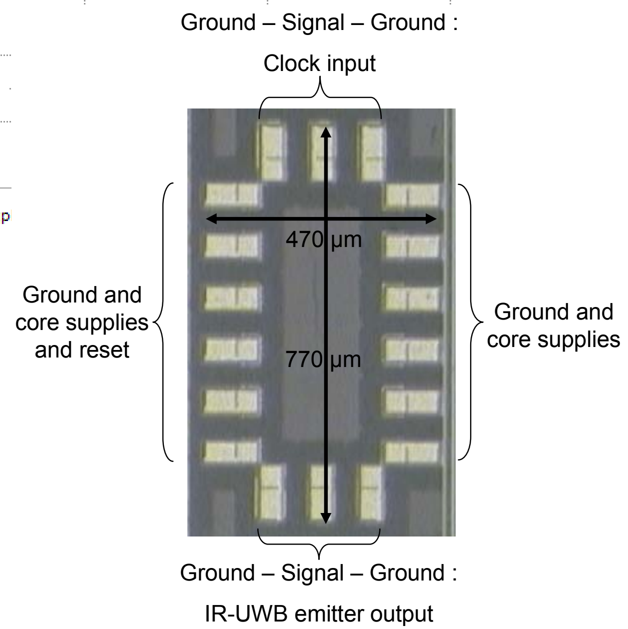
- Impulse radio UWB emitter – CMOS 65 nm STMicroelectronics technology
- Low complexity digital design : fast and reliable
- 1st prototype : without DAC, 1 bit output, OOK modulation
- 2nd prototype: reconfigurability in data rate, modulation, impulse forme, impulse duration. Data rate up to 1Gbps





UWB IR emitter performances





Measured results :

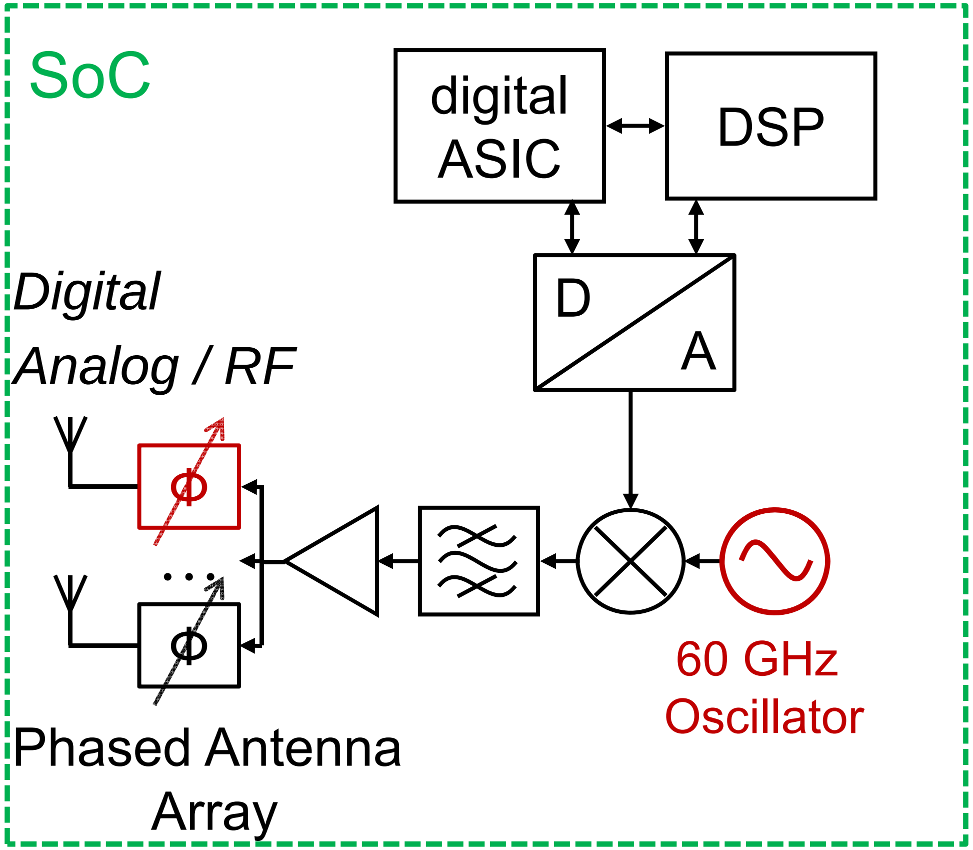
Data rate : 8 to 375 Mbits/s

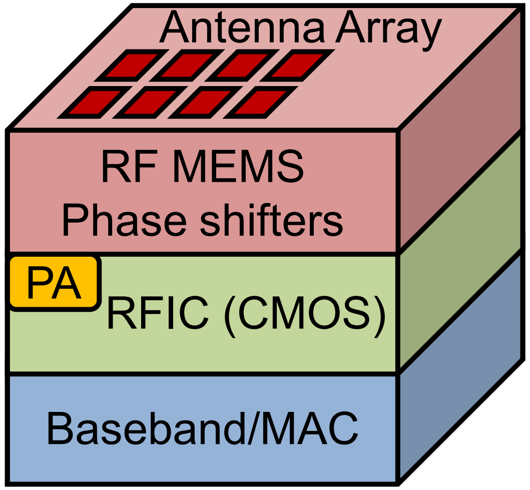
Tp : 20 ns to 720 ps

Consumption: 60 µW to 515µW

FOM: 7.23 to 1.4 pJ/bit

UWB-IR @ 60GHz



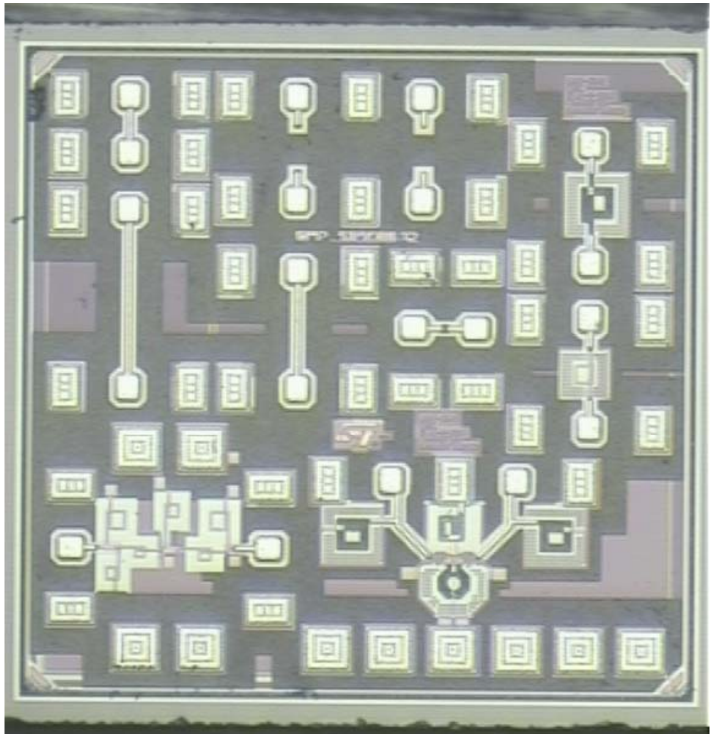


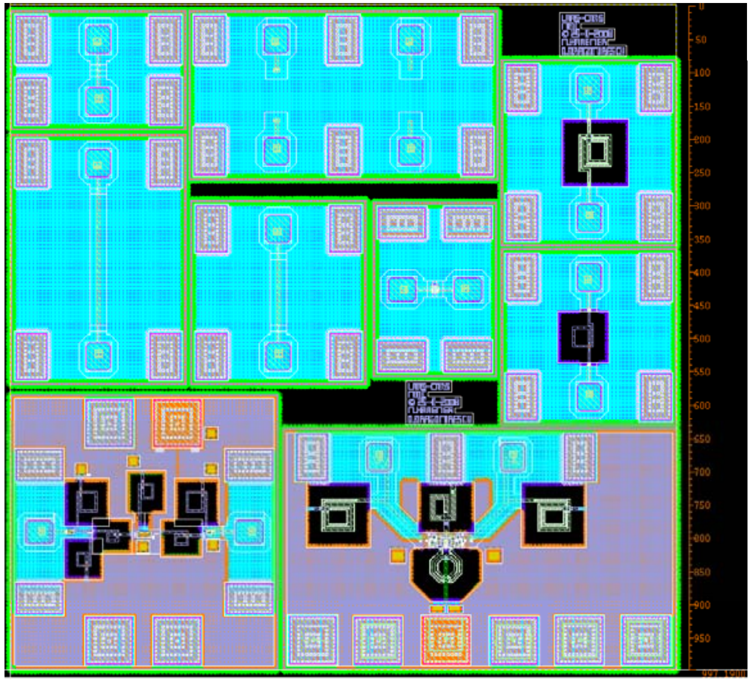
Modeling of entire heterogeneous system by connection of blocks described in VHDL-AMS

Advantages of this modeling approach

- Easily scalable in function of the design schema of the oscillator
- Easily scalable in function of the technology (SiGe, Si, BiCMOS, CMOS, CMOS SOI)
- Published in IEEE Transaction on MTT, April 2009

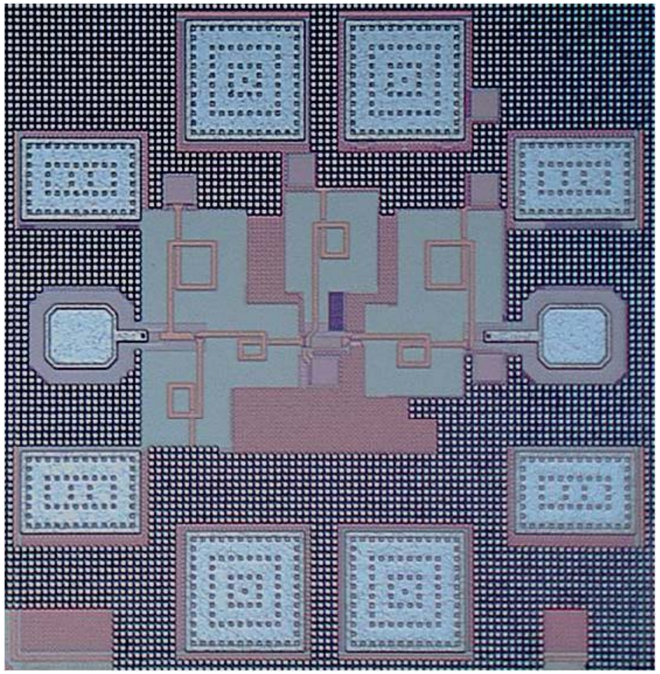
Low power CMOS ASICs @ 60GHz

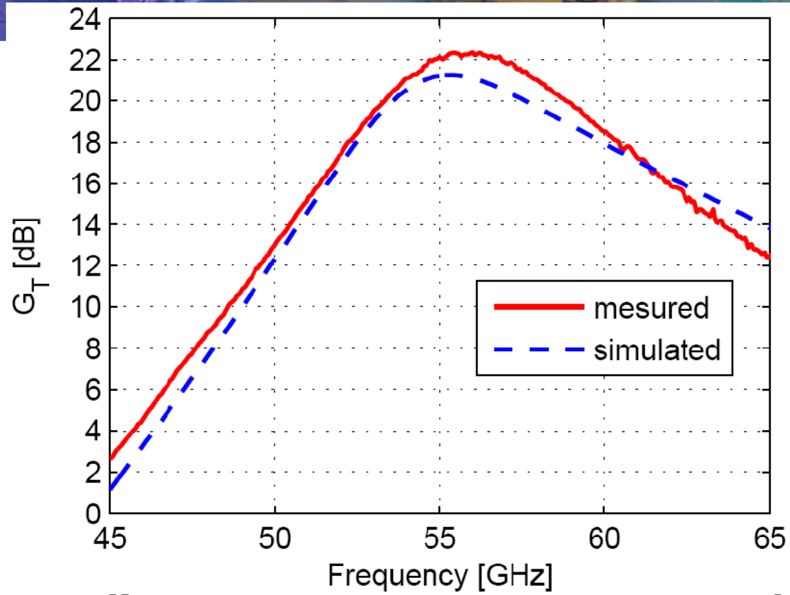


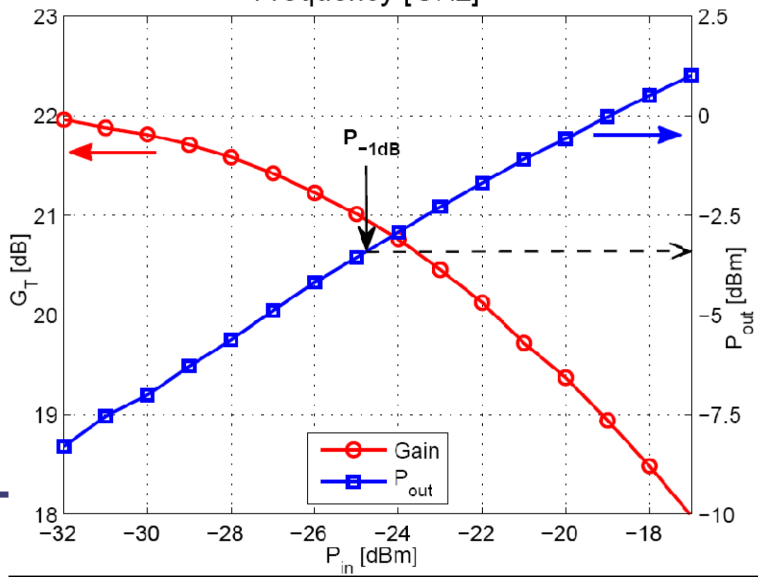


Technology : CMOS 65nm
LNA, VCO and mixer @ 60GHz
Inductances 60GHz : 50pH – 300pH

Low power CMOS LNA @60GHz





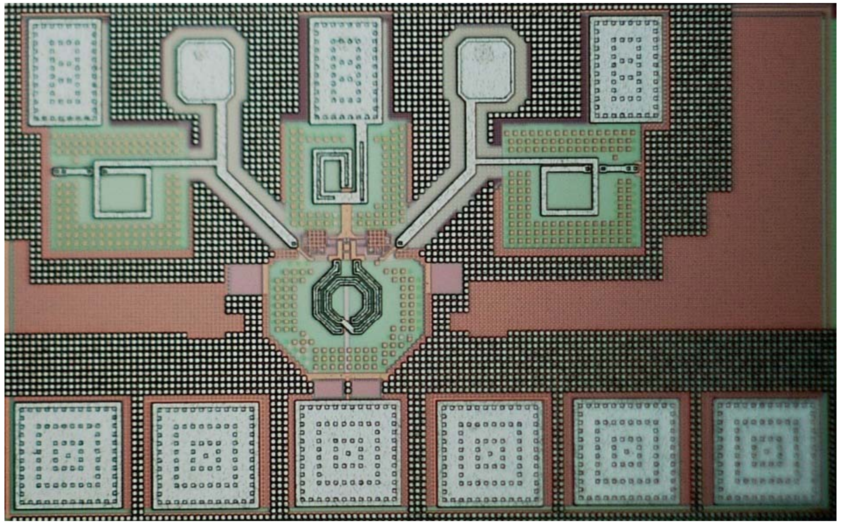


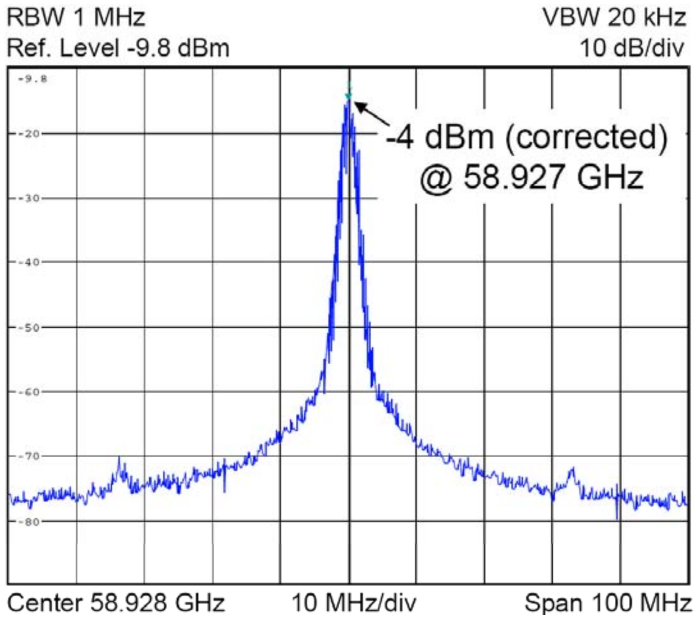
V=1.5V	V=1V
G_T=22.4dB	G_T=18.7dB
P_{-1dB}= -3.4dBm	P_{-1dB}= -6.5dBm

Power consumption:

P=16,8mW	P =8,5mW

High power efficiency CMOS VCO @60GHz





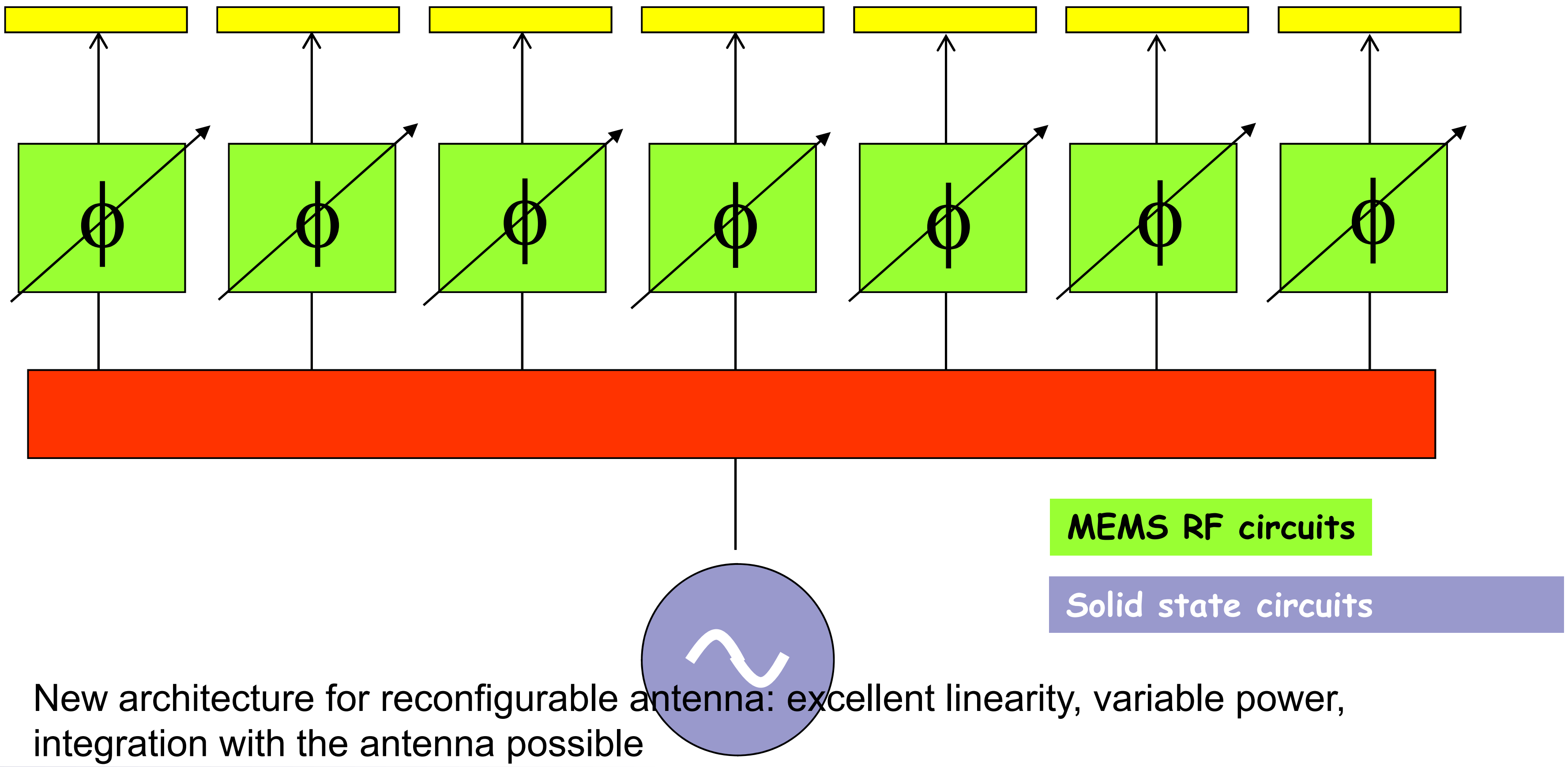
$P_{out\ diff} / P_{DC} = 3.65$

Measured single-ended VCO output at 1 V/16.5mA bias, $V_{control} = 0$ V

MEMS RF and Phase shifters @60GHz for smart antenna

Smart antenna : reconfigurable circuits @ 60GHz

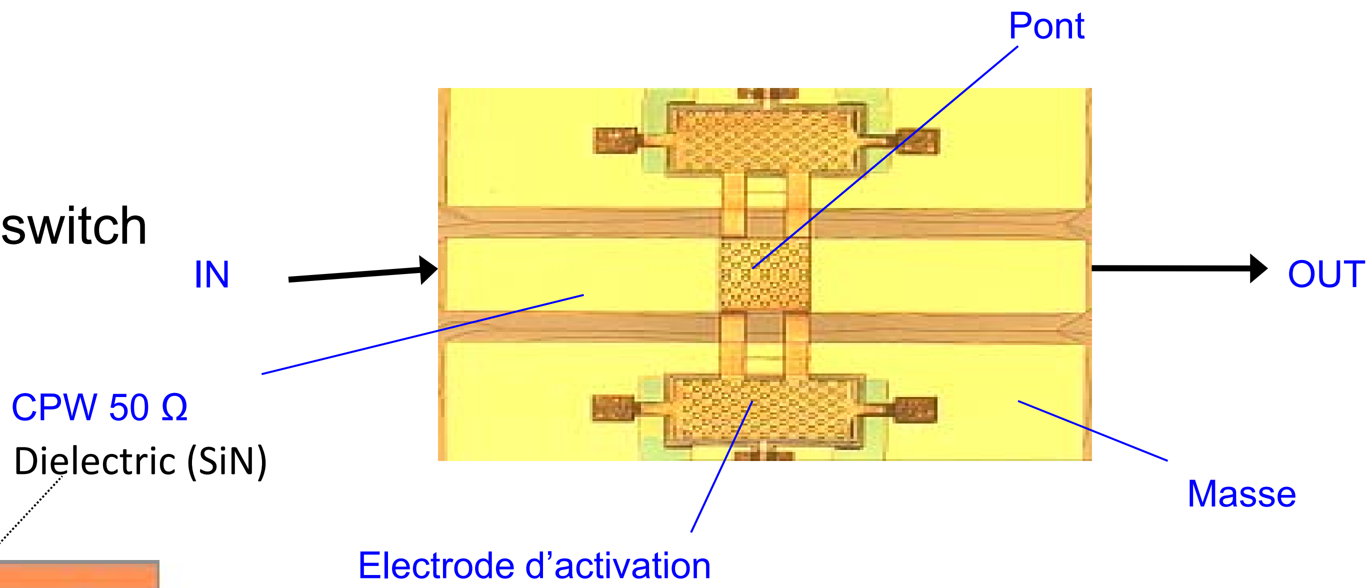
- Reconfigurable antenna in emission diagram and pointing direction.

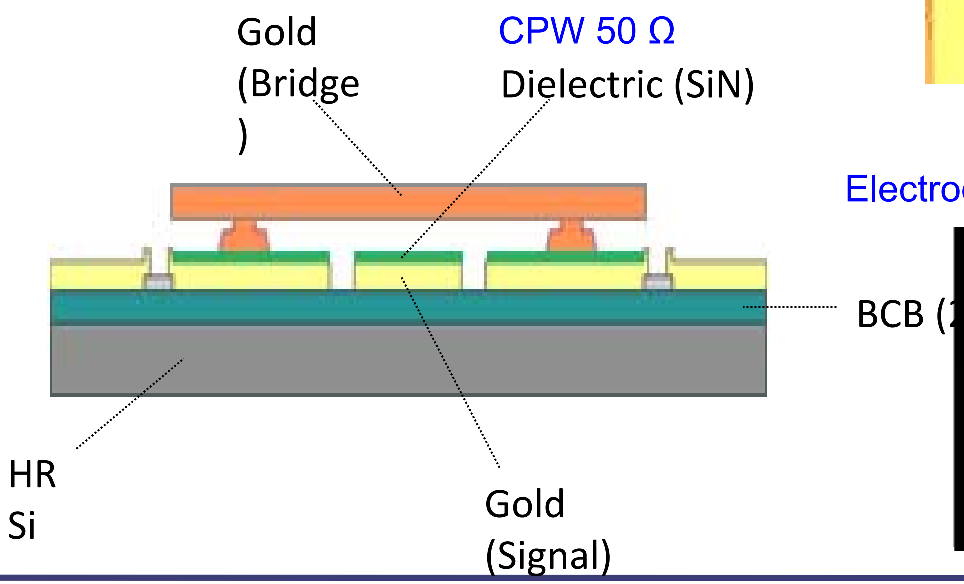


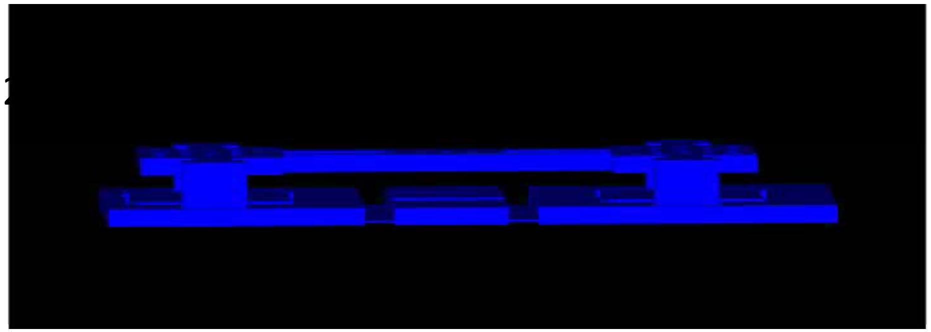
New architecture for reconfigurable antenna: excellent linearity, variable power, integration with the antenna possible

MEMS @ 60GHz

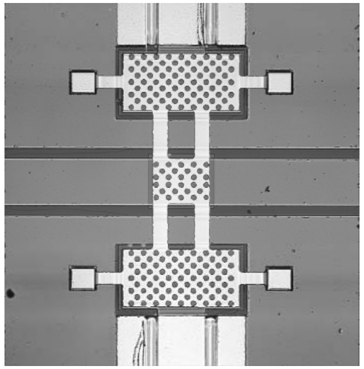
- MEMS RF
  - Capacitive switch



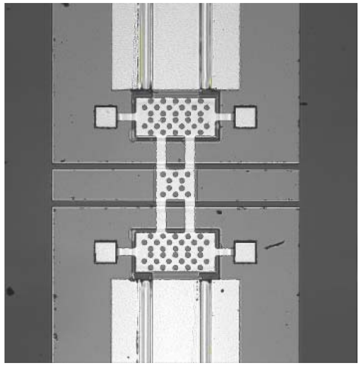




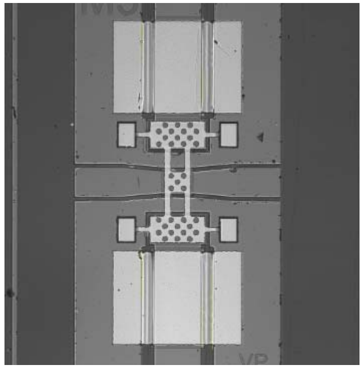
RF MEMS up to 94GHz in LAAS-CNRS technology



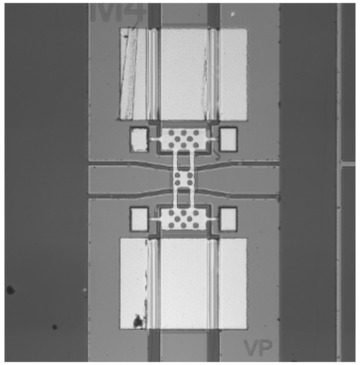
M1
(20-GHz MEMS)



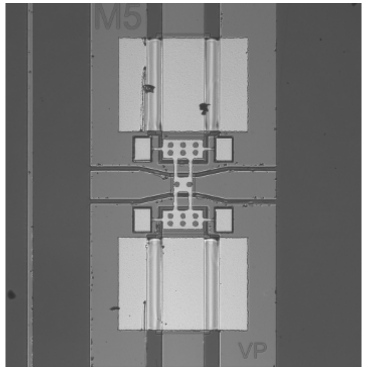
M2
(35-GHz MEMS)



M3
(60-GHz MEMS)



M4
(77-GHz MEMS)

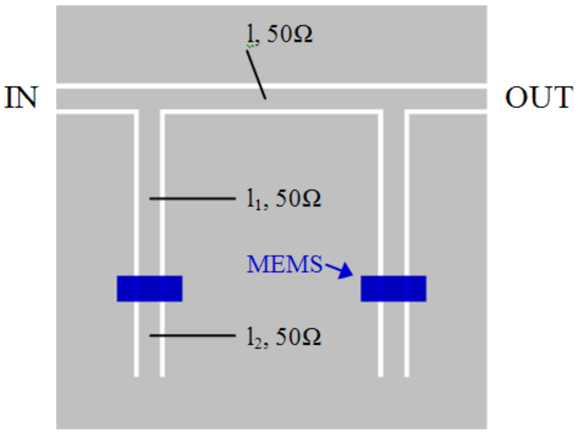


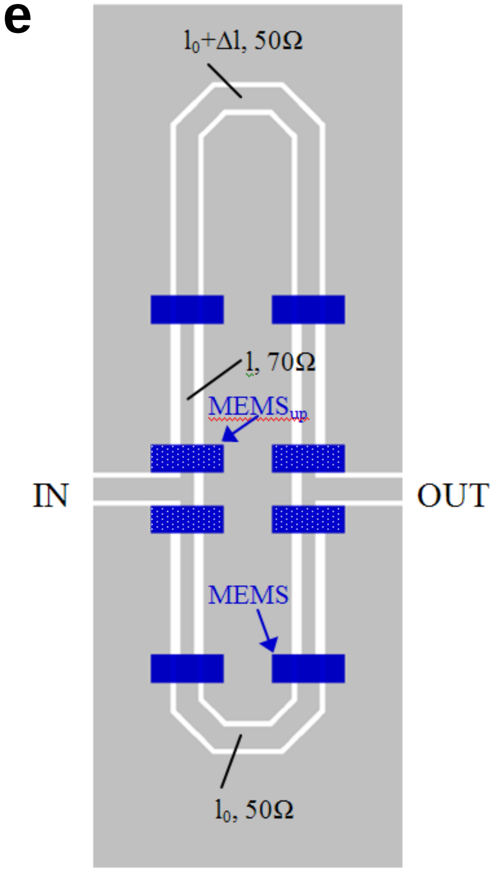
M5
(94-GHz MEMS)

IEEE Transaction on MTT in November 2009

Applications: 60-GHz Phase Shifters

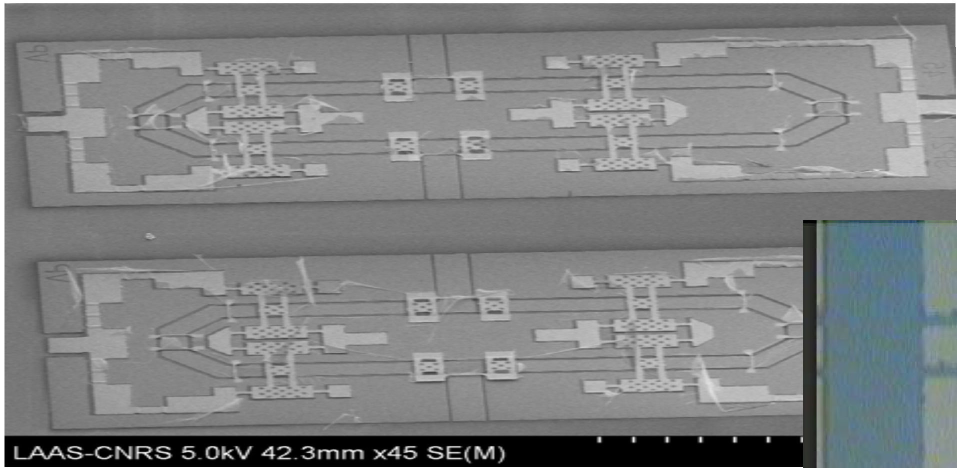
- Two versions of 1-bit phase shifters
  - **loaded-line / switched-line**

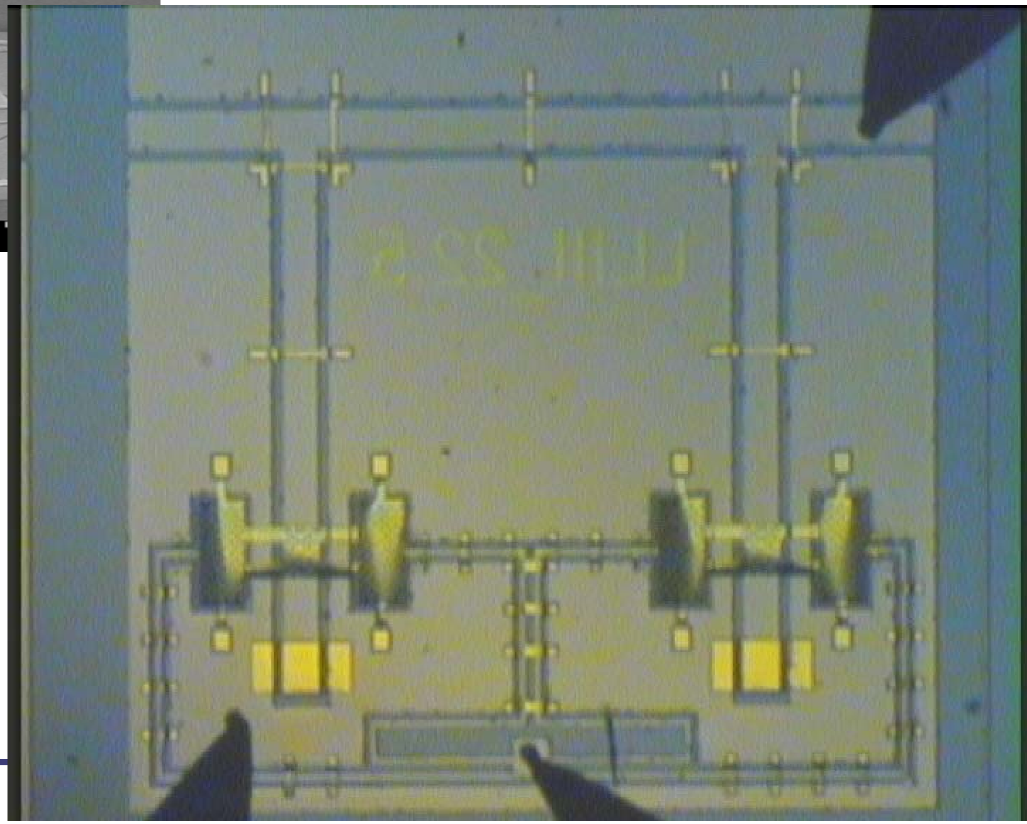




- At 60 GHz

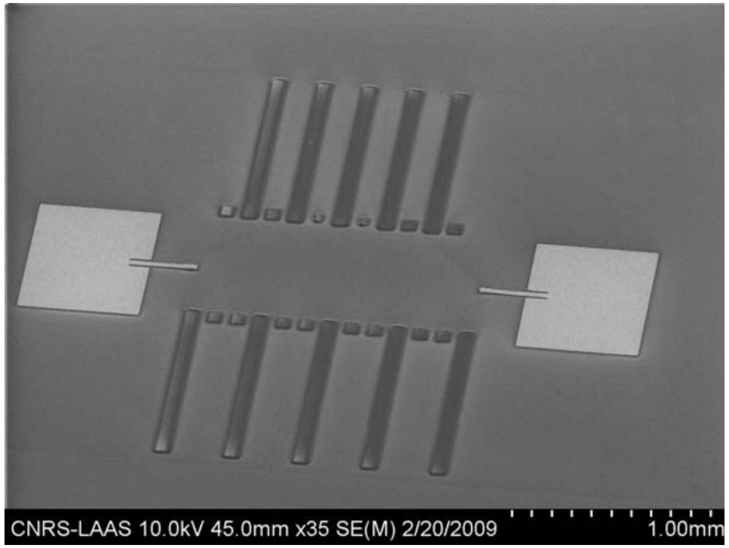
Fabricated Phase Shifter @ 60GHz



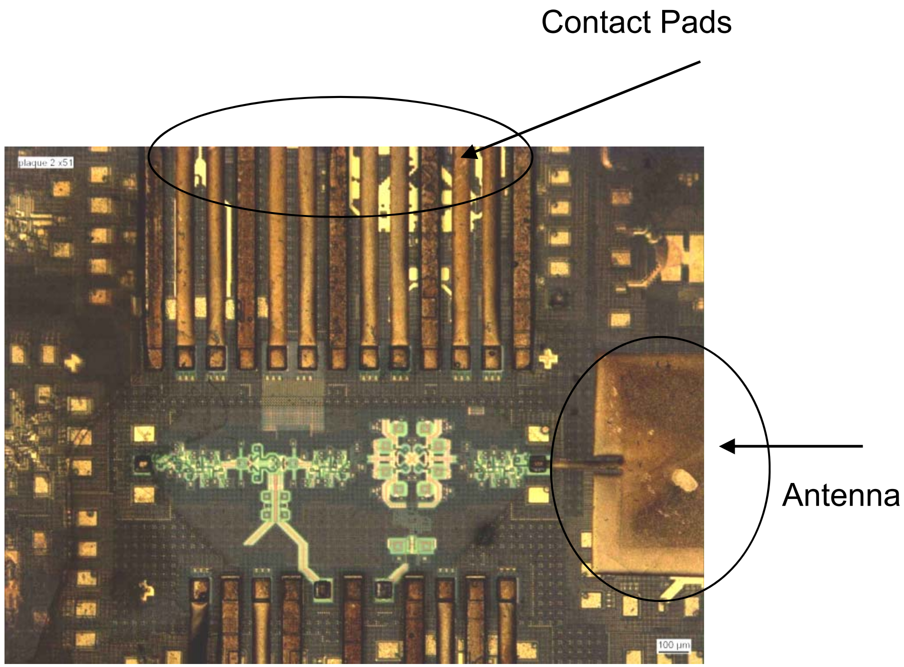


System integration

Above IC – antenna integration



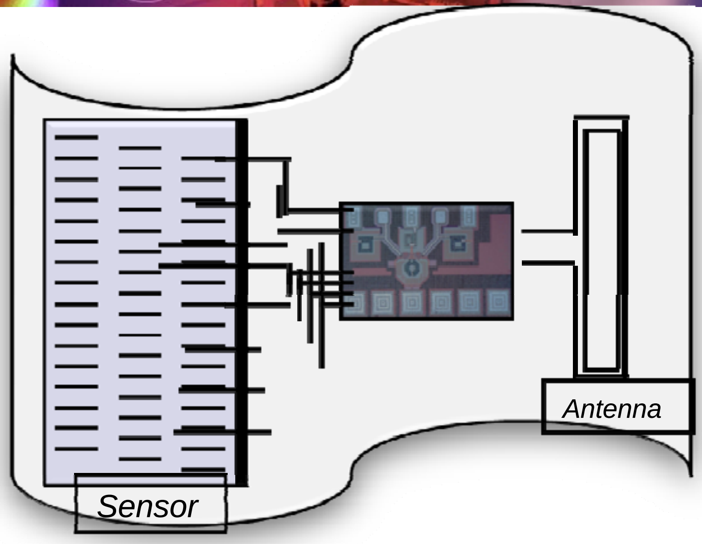
Antenna on test wafer

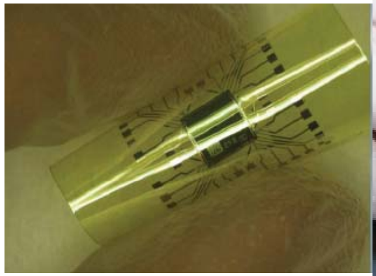


SiGE Transceiver and 3D integrated antenna

Collaboration with Toronto University: Prof. Sorin Voinigescu team

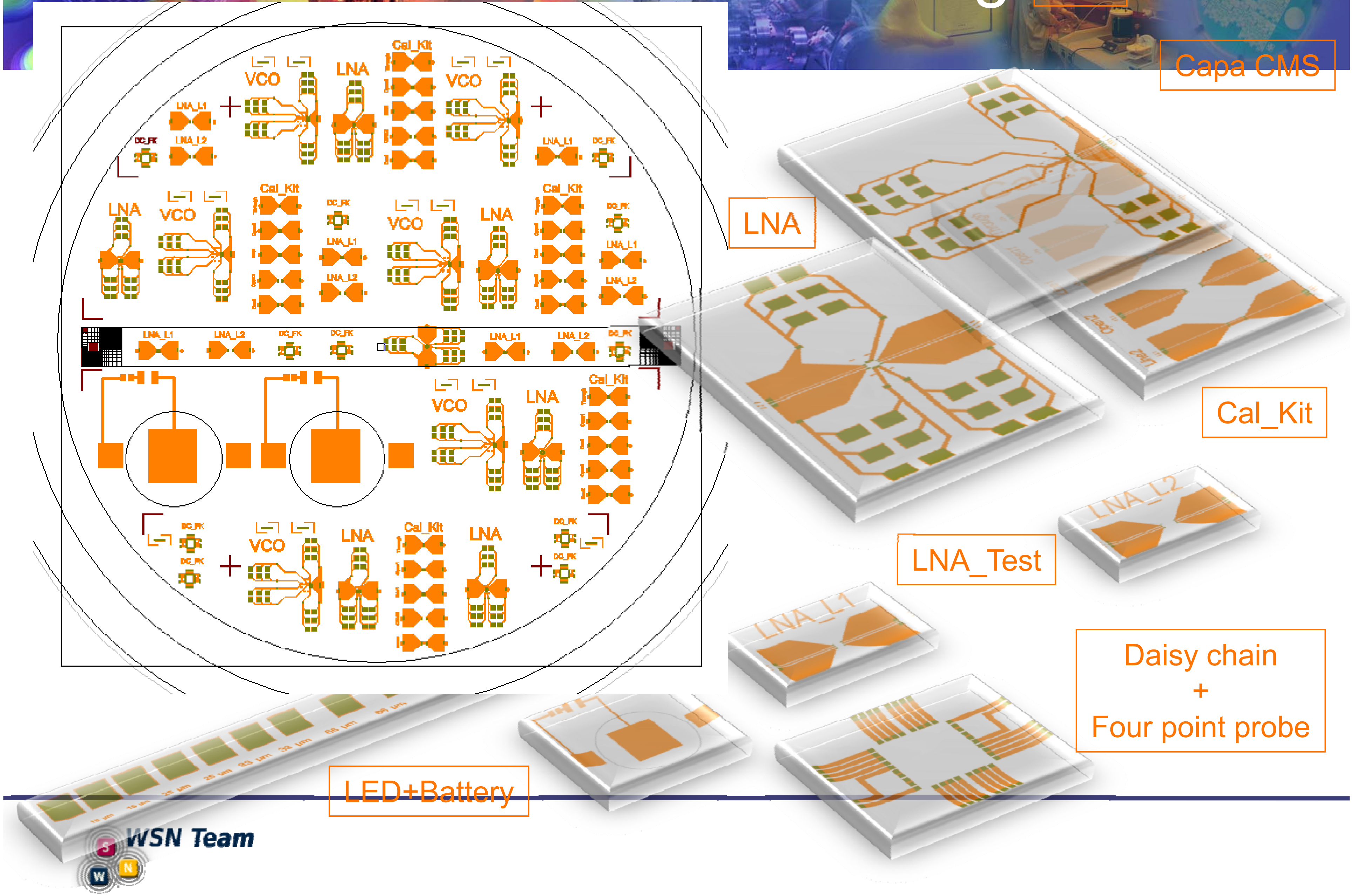
Flexible substrate integration





- Work in progress
- Substrate choice – Kapton 100HN
- Challenges:
- Antenna design
- Chip report, very small pads
- Process has to stay low temperature to not destruct the chip
- 60GHz integration
- Sensor on the same substrate
- Battery integration

Flexible substrate integration



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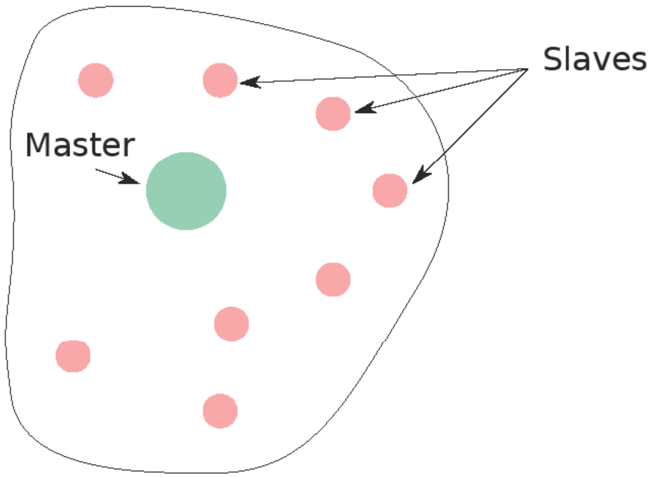
MAC layer and SYNCRONIZATION Cross-layering

ICN 2010 paper

T.Beluch, D. Dragomirescu and al. “Cross-layered Synchronization Protocol for Wireless Sensor Networks”

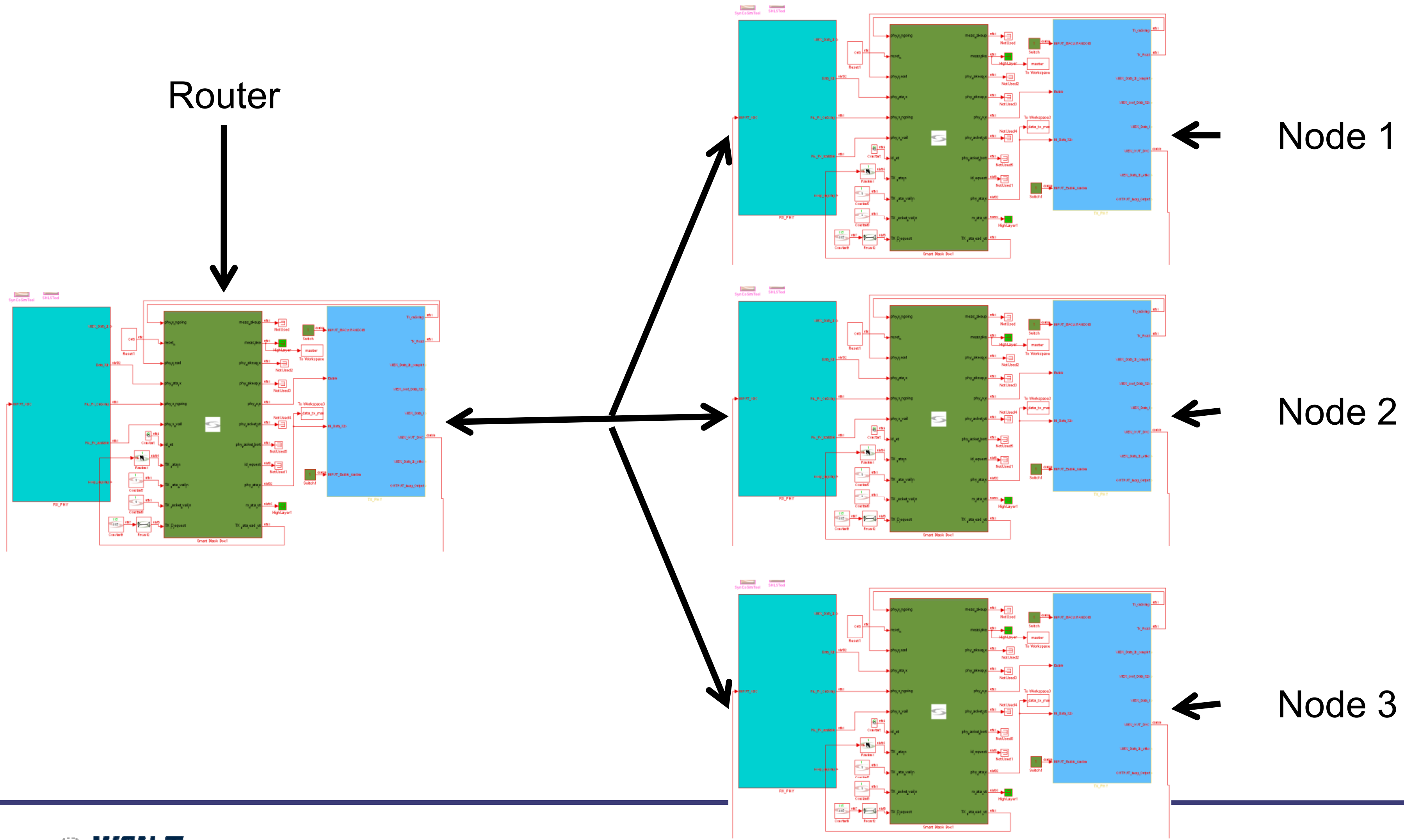
Synchronization for real time wireless measurement



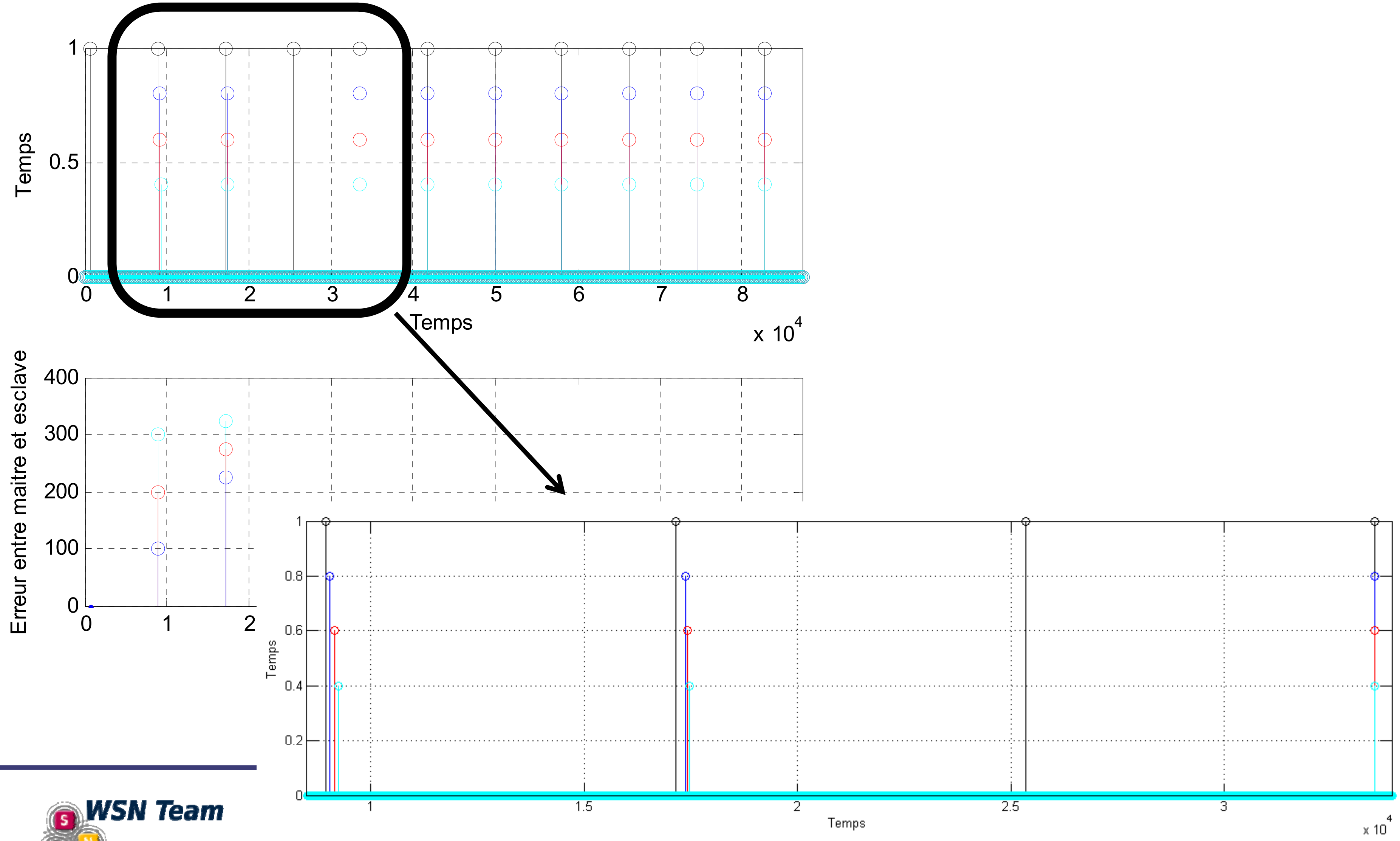
- Context:
  - Static cluster tree network
  - < 1us synchronization required

- Solution:
  - Deterministic TDMA
  - WiDeCS Sync Protocol – LAAS-CNRS solution

Router - nodes communication and synchronization



Synchronisation



Outline

- Objectives and specifications of cyber-physical systems for aeronautic applications
- Proposed solutions
  - Network architectures
  - Physical layer :digital base band, RF front end, frequency choice, smart antenna and integration – SoC approach
  - MAC layer and synchronization
  - Wireless Sensor Network simulator for aeronautic applications taking into account our hardware solutions

WSN simulator using UWB-IR

WSN using IR-UWB

- Objectives:
  - Predict the behavioral of a complex system with a high number of nodes
  - Determine the best network topology
- Impact of IR-UWB at network level :
  - Collisions
  - Power consumption
  - Simplicity
- Taken into account the specificity of IR-UWB physical layer in a network simulator
  - Discontinue emission
  - BER
  - Simplicity of MAC layer using IR-UWB

Simulator structure

Network simulator

	GloMoSim	NS-2	SensorSim	J-Sim	SENSE	OMNet
Fidélité	+++	++	++	+++	++	++
Parallélisme	Oui	Non	Non	Non	Non	Non
Modularité	+++	++	++	++	++	+++
Extensibilité	+++	+	-	++	++	+++
Scalabilité	+++	-	-	-	+++	+++
Réutilisabilité	+++	++	-	+++	++	++
Richesse	+++	+++	-	++	+++	+
Capteur	Non	Non	Oui	Oui	Oui	Non

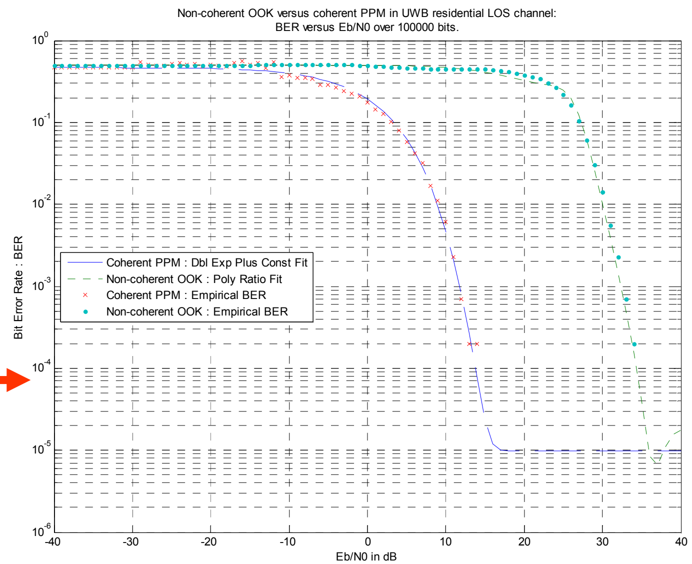
Glomosim :

1. Determine the power level received by the receiver
2. Consult the BER associated
3. Determine via the PER if the PDU is received or non

Behavior of physical layer IR-UWB is characterized via BER

Simulation Matlab

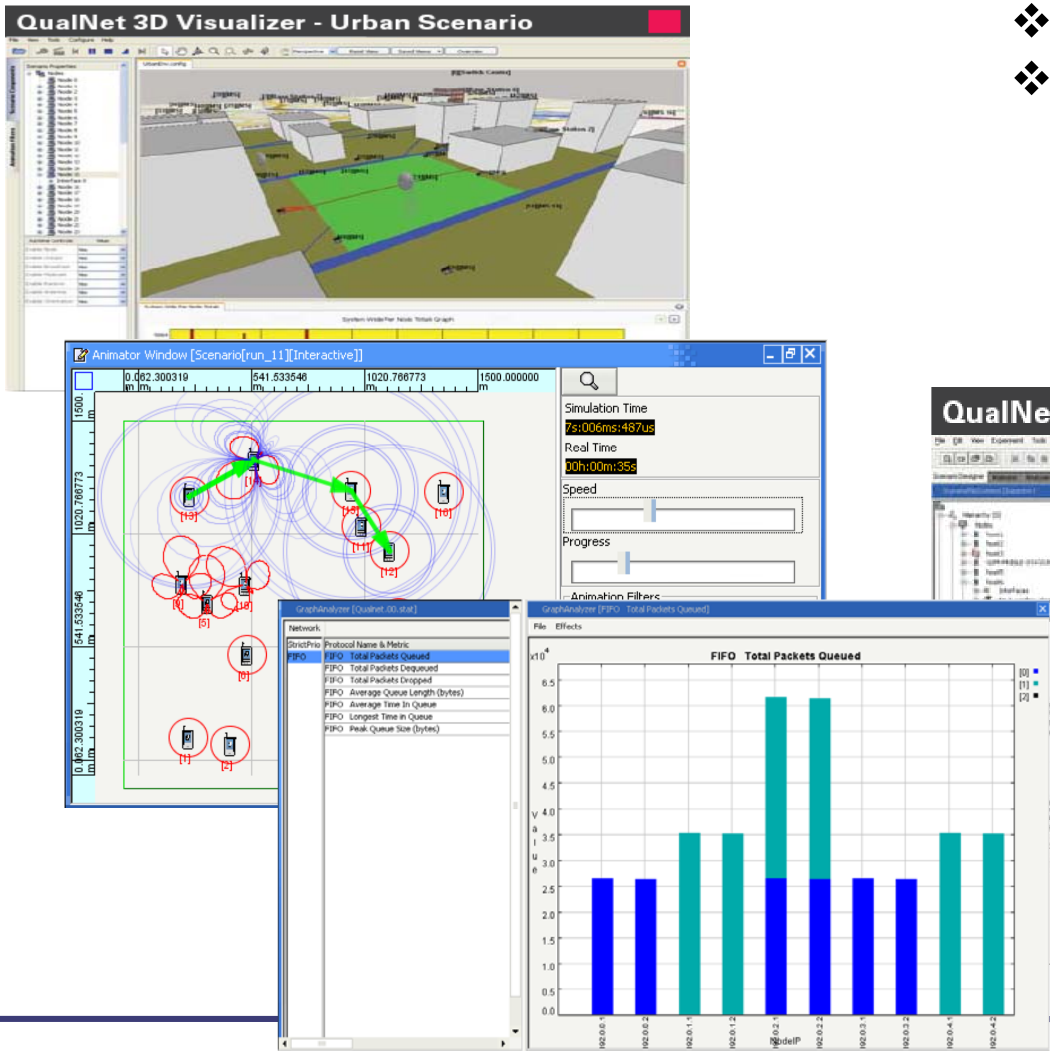
BER measurements on our transceivers

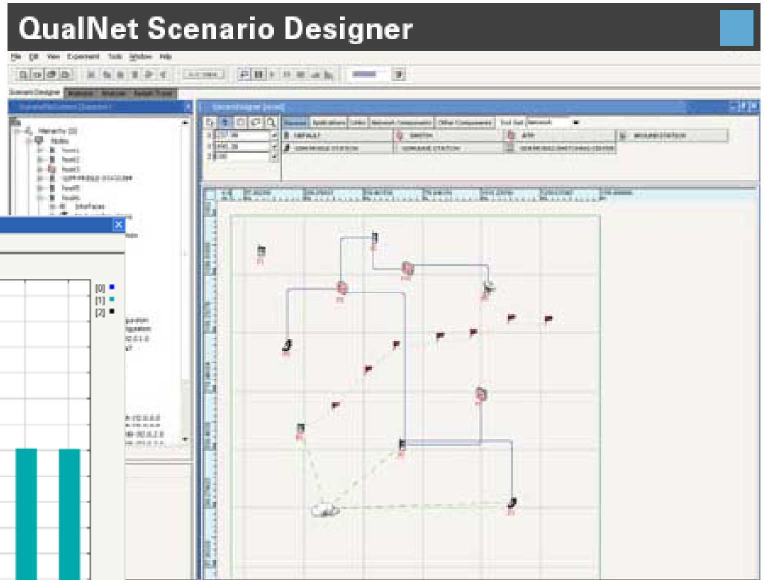


Laboratoire d'Analyse et d'Architecture des Systèmes

Wireless Sensors Networks Simulator

- ❖ Work in progress
- ❖ Qualnet Software
  - ❖ Real-time Simulation.
  - ❖ Designed for parallel execution
  - ❖ Packet tracer
  - ❖ 3D Visualization tool
  - ❖ Directive antenna included





Conclusion

- Cyber Physical System solution proposed for Aeronautic applications :
  - SoC Architectures -3D integration or flex substrate integration
  - UWB –IR reconfigurable emitter and receiver developed on FPGA
  - Impulse radio UWB emitter on ASIC developed → very low power
  - 60GHz architectures in progress on ASIC
  - VHDL-AMS models for RF front–end blocs and MEMS RF phase shifters →toward a SoC modeling
  - 60GHz MEMS RF designed and fabricated in LAAS technology
  - 60GHz phase shifter realized and measured
  - Cross-layering MAC –PHY
  - Synchronization
  - WSN simulator using UWB-impulse radio developed → determine the best network topology for one application

Thanks to WSN Team

- Professor : Daniela Dragomirescu (Assoc. Prof)
- Post-doc, Ph.D. students, engineers, Master students
  - Vincent Puyal – post-doc – MEMS RF and phase shifter design
  - Christina Villeneuve – post-doc – clean room technology for MEMS RF
  - Mehdi Jatlaoui – post-doc – flexible substrate integration
  - Samuel Charlot – research engineer - flexible substrate integration
  - Anthony Coustou – research engineer – CAD support and RF circuits design
  - Frederic Camps – research engineer – WSN simulator
  - Aubin Lecointre – Ph. D student – PHY and MAC layer for IR-UWB systems
  - Michael Kraemer –Ph.D student – 60GHz transceiver design and system modeling in VHDL-AMS
  - Julien Henaut – Ph.D. student – OFDM systems
  - Ali Kara Omar – Ph.D. student – RF transceiver @ 5GHz
  - Abdoulaye Berthe – Ph.D student – Mac layer
  - Thomas Beluch – Ph.D. student – MAC and synchronization protocol, low power transceivers
  - Mariano Ercoli –Ph.D. student - 60GHz transceiver design
  - Raphael Tocque – engineer – system modeling in VHDL-AMS
  - Florian Perget –Master student- MAC with beamforming algorithms
  - Stephane Coppola – Master student – phase shifter design

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- Further information and publications are available on our Website :

www.laas.fr\~daniela

Thank you for your attention !

Questions ?