Cyber-Physical Systems for Aeronautic Applications

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ICONS 2010
Toulouse – Aerospace Town
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
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
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 equipment

Rethinking the entire hardware – software system
In the far future – smart materials, composite materials → self-healing!

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.

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
- Precise identification of each sensor
- Precise synchronization of all sensor measures
- Deterministic MAC layer with synchronization algorithm

**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
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 localization)
  - 50 cm between seat rows, 70 cm large seat
  - Frequency >5 GHz
  - Smart antenna
  - Expected throughput ~1Mbit/s at least

- Wireless COTS solutions cannot be deployed in an aircraft
- Problems of frequency, availability and efficiency with such a number of nodes in such a small area - aircraft passenger cabin
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
Outline

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

- Proposed solutions
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  - MAC layer and synchronization
  - Wireless Sensor Network simulator for aeronautic applications taking into account our hardware solutions
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

Aircraft Network

Wireless Sensor nodes

Routers

Central computer

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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 NanolInnov – 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

- Low complexity circuits to be developed in CMOS technology → low cost, low power

- Challenges:
  - Channel estimation
  - Fast DAC/ADC
  - Reception synchronization
**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
★ 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
- 1\textsuperscript{st} prototype : without DAC, 1 bit output, OOK modulation
- 2\textsuperscript{nd} prototype: reconfigurability in data rate, modulation, impulse forme, impulse duration. Data rate up to 1Gbps
Measured results:

- Data rate: 8 to 375 Mbits/s
- $T_p$: 20 ns to 720 ps
- Consumption: 60 µW to 515 µW
- FOM: 7.23 to 1.4 pJ/bit
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
G_T=22.4dB
P_{-1dB}= -3.4dBm
Power consumption:
P=16.8mW

V=1V
G_T=18.7dB
P_{-1dB}= -6.5dBm
P =8.5mW

IEEE APMC dec. 2009
High power efficiency CMOS VCO @60GHz

\[ \frac{P_{\text{out diff}}}{P_{\text{DC}}} = 3.65 \]

Measured single-ended VCO output at 1 V/16.5mA bias, \(V_{\text{control}} = 0\) V
MEMS RF and Phase shifters @60GHz for smart antenna
Reconfigurable antenna in emission diagram and pointing direction.

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

Capacitive switch

- Gold (Bridge)
- CPW 50 Ω
- Dielectric (SiN)
- Electrode d'activation
- BCB (20µm)
- Masse
- Pont

HR Si
Gold (Signal)
RF MEMS up to 94GHz in LAAS-CNRS technology


IEEE Transaction on MTT in November 2009

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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

- VCO
- Flexible Substrate
- Capa CMS
- LNA
- Cal_Kit
- LNA_Test
- Daisy chain
- Four point probe
- LED+Battery
 Objectives and specifications of cyber-physical systems for aeronautic applications

 Proposed solutions
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MAC layer and SYNCRONIZATION
Cross-layering

ICN 2010 paper
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

Router

Node 1

Node 2

Node 3
Synchronisation

La figure montre deux graphiques. Le premier graphique représente la synchronisation du temps (Temps) sur l'axe des abscisses et la synchronisation du nombre d'erreurs (Erreur entre maître et esclave) sur l'axe des ordonnées. Les points en bleu et en rouge représentent les erreurs dérivées des maitres et des esclaves respectivement.

Le deuxième graphique, plus petit que le premier, présente les erreurs sur un plus petit échantillon. Il est orienté dans le sens des temps.
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WSN simulator using UWB-IR
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
Network simulator

Behavior of physical layer IR-UWB is characterized via BER

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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
Wireless Sensors Networks Simulator

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

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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 blocks 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
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  - Frederic Camps – research engineer – WSN simulator
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- Further information and publications are available on our Website:
  
  www.laas.fr/~daniela
Thank you for your attention!

Questions?