GRECO
Preliminary studies for autonomous systems

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**Agenda**

1. Overview of the project

2. Objectives and problematic of the project

3. State of the art
   - Energy harvesting
   - Protocols (PHY, MAC)
   - Power Manager

4. Use cases

5. Simulation environment

6. Conclusion & future works
1. Overview of the project

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6. Conclusion & future works
1. Overview of the project

- **GRECO: GREen Wireless Communicating Objects**
  A global approach for reducing consumption of energy autonomous communicating objects

- **ANR funded Project** (ARPEGE 2010 program)

- **Project duration**: 40 months (T0: 01/10/2010)

- **7 Partners**
  - 5 public research organisms: CEA-LIST, CEA-LETI, LEAT, IM2NP, IRISA
  - 1 PME: INSIGHT-SIP
  - 1 big industrial company: THALES (coordinator)
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2. Objectives and problematic of the project

- **Problematic:**
  - Designing communicating objects **autonomous in energy**
  - Existing techniques for reducing energy consumption can be applied at different levels:
    - Applicative, OS and Middleware, RF blocks, Supply voltage converters, etc.
    - Lack of visibility of these different techniques **interactions impacts**

- **Objectives:**
  - To propose a global approach of conception
    - Exploiting low power protocols
    - Designing and using low power circuits (RF, analog and digital)
    - Modeling an heterogeneous system
    - Defining a **Power Manager** that handles energy consumption and ensures that system will run properly: balancing energy consumed by the object VS. possible energy harvesting
2. Objectives and problematic of the project

- Principle for managing energy inside a node:
2. Objectives and problematic of the project

- Technologic and Scientific challenges:
  - Finding the right balance between required energy for application processing and possible harvested energy
    - Which kind of applications can be executed according to available energy scavenging?
    - Define a Power Manager
  - Heterogeneous models (interoperability issue)
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3. State of the art of Energy Harvesting

<table>
<thead>
<tr>
<th>Source d'énergie</th>
<th>Principe</th>
<th>Power density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumière</td>
<td>Photovoltaïque</td>
<td>6000 µW/cm²</td>
</tr>
<tr>
<td></td>
<td>Extérieur</td>
<td>(150 à 15000)</td>
</tr>
<tr>
<td></td>
<td>Photovoltaïque</td>
<td>6 à 20 µW/cm²</td>
</tr>
<tr>
<td></td>
<td>Intérieur</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Piezoelectrique</td>
<td>200 µW/cm²</td>
</tr>
<tr>
<td>Vibrations</td>
<td>Électrostatique</td>
<td>200 µW/cm²</td>
</tr>
<tr>
<td></td>
<td>Électromagnétique</td>
<td>10 µW/cm²</td>
</tr>
<tr>
<td>Gradient thermique</td>
<td>Température</td>
<td>60 µW/cm² (? T=10°C)</td>
</tr>
<tr>
<td>Champ électromagnétique</td>
<td>Antenne résonnante</td>
<td>0.3 µW/cm² (E=1 V/m)</td>
</tr>
<tr>
<td>Bruit acoustique</td>
<td>Onde acoustique</td>
<td>0.003 µW @ 75dB</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 µW @ 100dB</td>
</tr>
</tbody>
</table>

C. Condemine – CEA-LETI : Energy Autonomous Systems become achievable thanks to progress in Design & Technology with a global system approach according to the target application.
3. State of the art of Protocols

- Check standards and components according to targeted applications in terms of:
  - Power consumption
  - Throughput
  - Range
  - Sensibility
  - Robustness (interferers, fading, ...)

### 3. State of the art of Protocols

- **Wireless low power radio standards**
  - IEEE 802.15.4, Bluetooth LE, IEEE 802.15.6-NB, IEEE 802.15.4a, IEEE 802.15.6-UWB, DAsh7, Z-Wave, Miwi, ...

<table>
<thead>
<tr>
<th></th>
<th>Bluetooth</th>
<th>BLE</th>
<th>IEEE 802.15.4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coût d’un module</strong></td>
<td>$3</td>
<td>TBA</td>
<td>$2</td>
</tr>
<tr>
<td><strong>Topologie du réseau</strong></td>
<td>Ad hoc, point à point, étoile</td>
<td>Ad hoc, point à point, étoile</td>
<td>Mesh, ad hoc, étoile</td>
</tr>
<tr>
<td><strong>Sécurité</strong></td>
<td>128-bit</td>
<td>128-bit</td>
<td>128-bit</td>
</tr>
<tr>
<td><strong>Temps de réveil et émission</strong></td>
<td>3 s</td>
<td>TBA</td>
<td>15 ms</td>
</tr>
<tr>
<td><strong>Bande</strong></td>
<td>2.4 GHz</td>
<td>2.4 GHz</td>
<td>2.4 GHz, 868 MHz, 915 MHz</td>
</tr>
<tr>
<td><strong>Antenne</strong></td>
<td>Partagée</td>
<td>Indépendante</td>
<td></td>
</tr>
<tr>
<td><strong>Consommation</strong></td>
<td>100 mW</td>
<td>10 mW – 30 mW</td>
<td>30 mW – 50 mW</td>
</tr>
<tr>
<td><strong>Durée de vie de la batterie</strong></td>
<td>Jours ~ Mois</td>
<td>1 – 2 ans</td>
<td>6 mois – 2 ans</td>
</tr>
<tr>
<td><strong>Portée (@ 0dBm)</strong></td>
<td>10 m – 30 m</td>
<td>10 m</td>
<td>10 m – 75 m</td>
</tr>
<tr>
<td><strong>Débit</strong></td>
<td>1 – 3 Mbits/s</td>
<td>1 Mbits/s</td>
<td>25 – 250 Kbits/s</td>
</tr>
</tbody>
</table>
3. State of the art of Protocols

- **Wireless low power radio components**
  - IEEE 802.15.4 compatible
    - CC2420 family
    - LETIBEE
  - Bluetooth LE compatible
    - CC2540
    - nRF8001
  - IEEE 802.15.4a (UWB) compatible
    - DAsh7, Z-Wave, Miwi, ...
3. State of the art of Protocols

- **802.15.4 compatible radio modules**

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Data buffer (bits)</th>
<th>Sleep (µW)</th>
<th>Idle (mW)</th>
<th>RX (mW)</th>
<th>TX (mW)</th>
<th>Sensibility (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TI</td>
<td>CC2420</td>
<td>128</td>
<td>0.005</td>
<td>1</td>
<td>50.7</td>
<td>47</td>
<td>-95</td>
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<tr>
<td>TI</td>
<td>CC2400</td>
<td>32</td>
<td>4</td>
<td>3.2</td>
<td>64.8</td>
<td>51</td>
<td>-87</td>
</tr>
<tr>
<td>TI</td>
<td>CC2500</td>
<td>64</td>
<td>0.7</td>
<td>2.7</td>
<td>30.6</td>
<td>38.1</td>
<td>-82</td>
</tr>
<tr>
<td>Microchip</td>
<td>MRF24J40</td>
<td>128</td>
<td>3.4</td>
<td>-</td>
<td>30</td>
<td>37.4</td>
<td>-91</td>
</tr>
<tr>
<td>Nordic</td>
<td>nRF2401A</td>
<td>32</td>
<td>2.47</td>
<td>0.02</td>
<td>51.3</td>
<td>35.7</td>
<td>-85</td>
</tr>
<tr>
<td>Nordic</td>
<td>nRF24L01</td>
<td>32</td>
<td>2.7</td>
<td>0.09</td>
<td>36.9</td>
<td>33.9</td>
<td>-82</td>
</tr>
<tr>
<td>Atmel</td>
<td>AT86RF230</td>
<td>128</td>
<td>0.05</td>
<td>-</td>
<td>41.8</td>
<td>44.5</td>
<td>-101</td>
</tr>
<tr>
<td>ST</td>
<td>SN250</td>
<td>128</td>
<td>5.7</td>
<td>-</td>
<td>102.6</td>
<td>102.6</td>
<td>-97</td>
</tr>
<tr>
<td>Jennic</td>
<td>JN5139</td>
<td>192</td>
<td>7.5</td>
<td>-</td>
<td>107.3</td>
<td>107.3</td>
<td>-96</td>
</tr>
<tr>
<td>Panasonic</td>
<td>PAN4551</td>
<td>4000</td>
<td>0.8</td>
<td>-</td>
<td>104</td>
<td>60.5</td>
<td>-98</td>
</tr>
<tr>
<td>Redwire</td>
<td>Redbee</td>
<td>-</td>
<td>3.3</td>
<td>-</td>
<td>75</td>
<td>90</td>
<td>-100</td>
</tr>
</tbody>
</table>

⇒ Tradeoffs between power consumption and performance
3. State of the art of Protocols

- **Wireless low power MAC protocols**
  - 2 kinds of approaches for medium access
    - Reservation: requires nodes synchronization but better throughput and guaranteed delay
    - Contention: less constraints but lower throughput
  - Optimizing power has an impact on throughput, robustness and delay
  - In MAC protocol domain, different parameters limit the power efficiency of the network
    - Collisions
    - Overhearing (frames received that do not concern the node)
    - Signaling frames (control and synchronization): power cost for extra information
    - Idle listening: a node tries to detect if a frame has been sent for him
      ➔ Main overhead for low traffic network
    - Network Interferences (co-channel, adjacent, intermodulation...) or linked to the ISM band (microwaves...)
3. State of the art of Protocols

- "Classical" solutions to improve power efficiency
  - Collision
    - CSMA (Carrier Sense Multiple Access) with different alternatives (CSMA/CA, CSMA/ARC, ...)
    - Slotted CSMA/CA Random backoff period used in 802.15.4 for instance
  - Overhearing
    - Destination address filtering or use a different channel for signaling frames
  - Idle listening
    - Some protocols propose low power modes: radio (in RX) can be switched off over a long period...
3. State of the art of Protocols

- “Classical” solutions to improve power efficiency (cont.)
  - Reducing TX power when possible (then interference level as well)
3. State of the art of Power Managers

- **Main techniques:**
  - **DPM**: alternating periods of sleep and active (listen)
  - **DVFS**: adapt the power supply and operating frequency to match the workload. *Definition of operating point: energy efficiency according to switch time, DC/DC converter, battery level ...*
  - **Radio**:
    - Kind of modulation,
    - Power amplifier tuning ....

![Diagram showing consumed power vs. Tx power level for different modulation schemes.](image)
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4. Use cases

5. Simulation environment

6. Conclusion & future works
4. SHM use case

- **Structure Health Monitoring**
  - An electronic box attached to an equipment for monitoring its communication system
  - **Objective**: prevent possible failures and dysfunctions
  - Example of use: handling rail signaling
  - This object is composed of 3 modules:
4. Smart building use case

- **Sensor networks for smart buildings**
  - Metrics to measure: temperature, brightness, humidity, electrical consumption, intruder detection...
  - **Objective**: to define a small sensor network autonomous in energy for future smart buildings
  - This application will be based on the Bluetooth Low Energy (BT LE) standard protocol
  - A demo board including a master station and several slaves with at least 2 sensors (temperature and humidity) will be designed.
  - Each object is composed of the following modules:
    - RF module based on BT LE
    - Microprocessor
    - One or several sensors
    - Energy source
4. AUDIO use case

- **Wireless audio communication**
  - A wireless communicating object enabling audio frames transmission and reception between nodes of a PAN
  - **Objective**: to guarantee a minimum quality of service of the audio communication
  - Example: fireman urgency system
  - This object is composed of the following modules (except energy source & battery):
4. Use case

- **Technical approach**
  - Case study definition and specification
  - Characterization of constraints and requirements (QoS) with corresponding energetic balance
  - Integration of models within simulation infrastructure and/or prototyping under real hardware platforms
  - Evaluation of the power manager
4. Use case

- **Example of constraints for the audio application**
  - Constraints from external environment (solar panel in our case): what is the possible quantity of harvested energy?
    - Lighting conditions: intensity and type
    - **80 µW** @ 200 Lux and **350 µW** @ 1000 Lux (values given for fluorescent light conditions)
  - Structural and functional constraints: node architecture
    - MSP430: 3 to 13mW in active mode, up to 50µW in Idle
    - CC2500: TX power from -30 to +1dBm (33mW @ -12 dBm, 63mW @ 0dBm)
    - Etc.
  - System Constraints
    - Network topology
    - Throughput
4. Use case

- Example of requirements (QoS) for the audio application
  - Good audio quality (audible)
  - Minimum communication duration (depends on battery level, light conditions, time of the day...)
  - Maximum distance between 2 nodes (a receiver and an emitter)
  - Maximum latency
  - Mobility handling
  - Maximum movement speed of the communicating object
4. Use case

- **Two operational modes for audio application (QoS)**
  - **Low mode**
    - A degraded mode in terms of QoS
    - Used when battery is low or when energy harvested is less important than required operating energy
    - Mode with minimum functionalities
    - Lowest CPU load, then energy consumption
  
  - **Medium mode:**
    - Mode with more functionalities
    - More constraints in terms of QoS (audio quality, latency...)
    - Communications not limited to 10 seconds
4. Use case

- **Two operational modes for audio application (QoS)**
  - Each mode is characterized by:
    - Communication duration and period
    - Limited TX power (then distance)
    - Latency
    - Mobility handling...
  
  - This is the power manager that will be in charge of exploiting these modes
    - Nodes (or part of nodes) will be switch off/on depending on transmission needs
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5. Simulation environment

- **Objectives**
  - A global model of the communicating object
  - Identify an adapted simulation and modeling infrastructure
  - Validate the whole system using significant test sequences and relevant models of propagation channel and networks

- **Challenges**
  - Heterogeneous type of models: RF, analog, digital, energy harvester, battery...
    - interoperability of models
  - Relationship between functional, timing and energy behaviors
    - need for relevant abstractions of both behavior (functional) and energy (power consumption)
  - Evaluate the power manager to efficiency handle the balance between energy harvested and consumed of the system
    - Select the most adapted simulation environment to integrate and simulate developed models
5. Simulation environment

- **Output**
  - information feedback on power consumption, BER, maximum throughput, etc.
  - adapt if necessary specifications of the communicating object to balance energy harvested and consumed

- **Existing modeling languages**
  - SystemC, SystemC/AMS, ...

- **Simulation platform candidates**
  - Ns-2
  - WsNet/Wsim
  - Omnet++
  - ...

Pros:
- Detailed existing MAC models (detailed 802.15.4)
- Simulation description using XML
- Energy models available (for RF transceiver only) and validated
- Large development community (reactive forum)

Cons:
- Limited propagation models
- Need to add energy and functional models of node, battery, energy harvester...
- Modifying Ns-2 is not “peanuts”
WsNet/WSim

**Pros:**
- Network simulator (WSNet) coupled to node simulator (WSIM)
- Detailed propagation model (pathloss, fading, shadowing, interferer position and relative power)
- Co-simulation with Matlab possible (socket communication developed by CEA/LETI)
- Code modularity

**Cons:**
- Limited development community
- Co-simulation with SystemC possible but would require additional development time.
- No graphical runtime environment
- Energy module connected only to radio module!
- Limited version of 802.15.4 MAC layer (beaconless only)
Pros:
- Detailed existing MAC models (detailed 802.15.4)
- Simulation description using NED language (Java-style package system)
- Graphical runtime environment
- Co-simulation with Matlab possible (using MATLAB API developed by CEA-LETI)
- SystemC integration allowed using OMNEST (commercial version of OMNet++)
- Large development community (reactive forum)

Cons:
- Choice of Framework: choose between MIXIM, Mobility Framework, INETMANET, Castalia, etc.
- Enhanced PHY layer should be developed
- Associated node simulator?
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6. Conclusion and future works

- GRECO is just 6 months old
- Good synergy between all partners
- First studies are encouraging

- More accurate energetic balance for the different use cases will be performed
- Simulation platforms evaluation on progress
- Specification of the communicating objects and power manager