Overview of learning and decision making techniques for cognitive radio equipment

Wassim JOUINI, Christophe MOY, Jacques PALICOT

Supélec, Rennes Campus

Team SCEE/IETR CNRS-6164

christophe.moy@supelec.fr

Lab

- **Christophe MOY**
- **Professor in SUPELEC, Rennes campus**
- **SUPELEC is a French engineering school**
- **SCEE research team – Jacques PALICOT**
  - 7 professors, 12 Ph.D. students
  - Research topics: SDR and CR
  - 3 axes
    - Signal processing and decision making
    - Hardware architectures and design methodologies
    - Sensing for cognitive radio

Presentation outline

- **Cognitive Radio introduction**
- **Decision making for CR**
- **HDCRAM**
- **CR equipments high-level design**
- **Conclusion**

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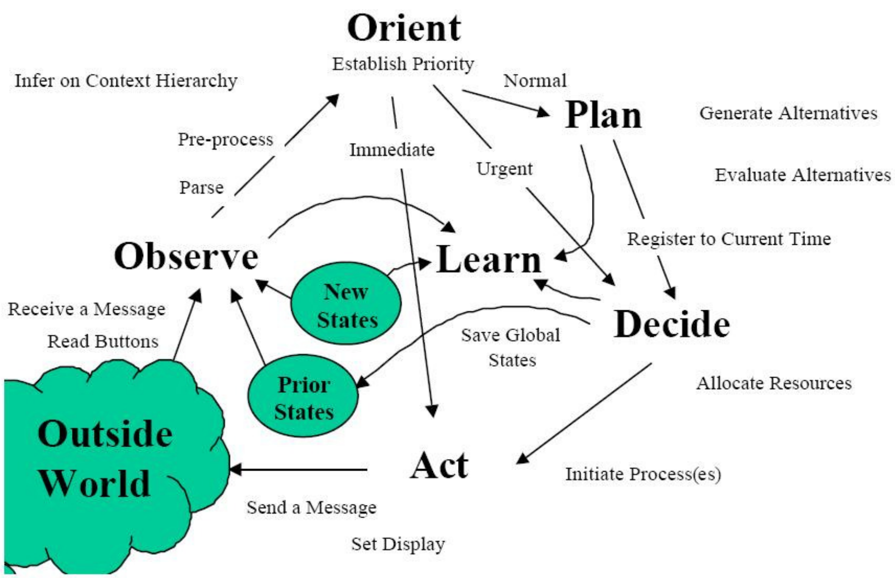
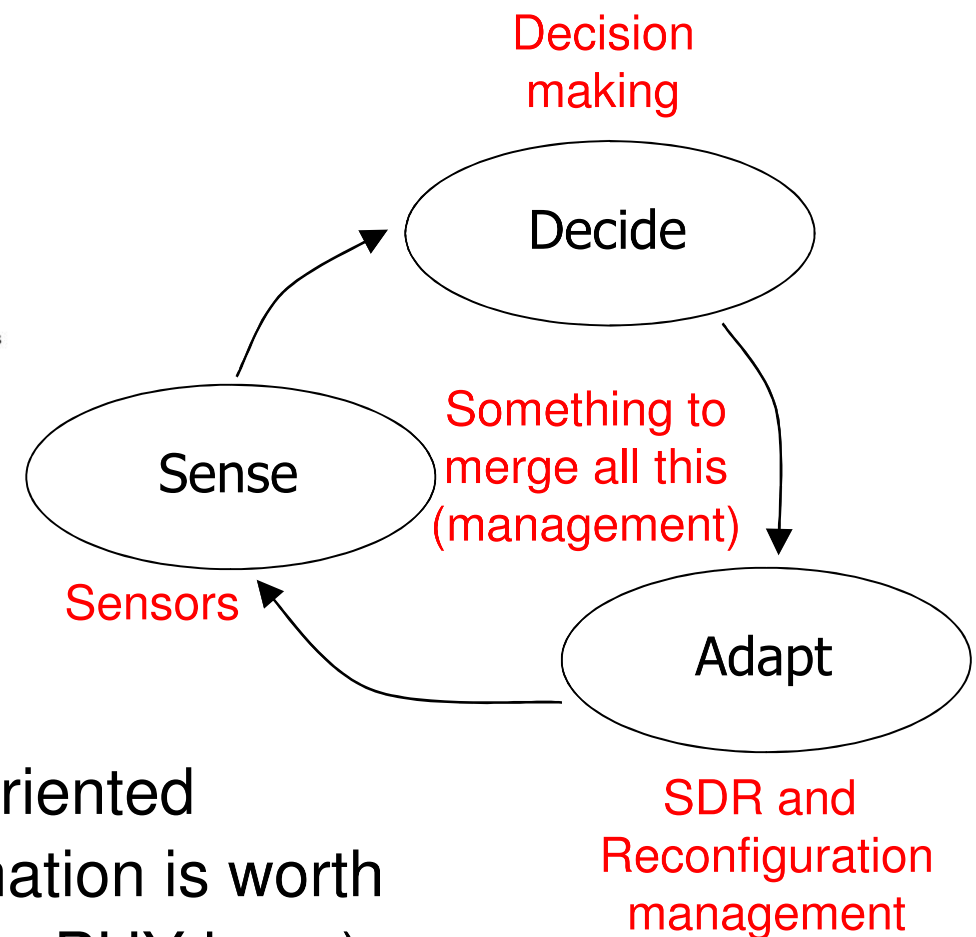
Simplified cognitive cycle

- **Joe MITOLA's cycle**



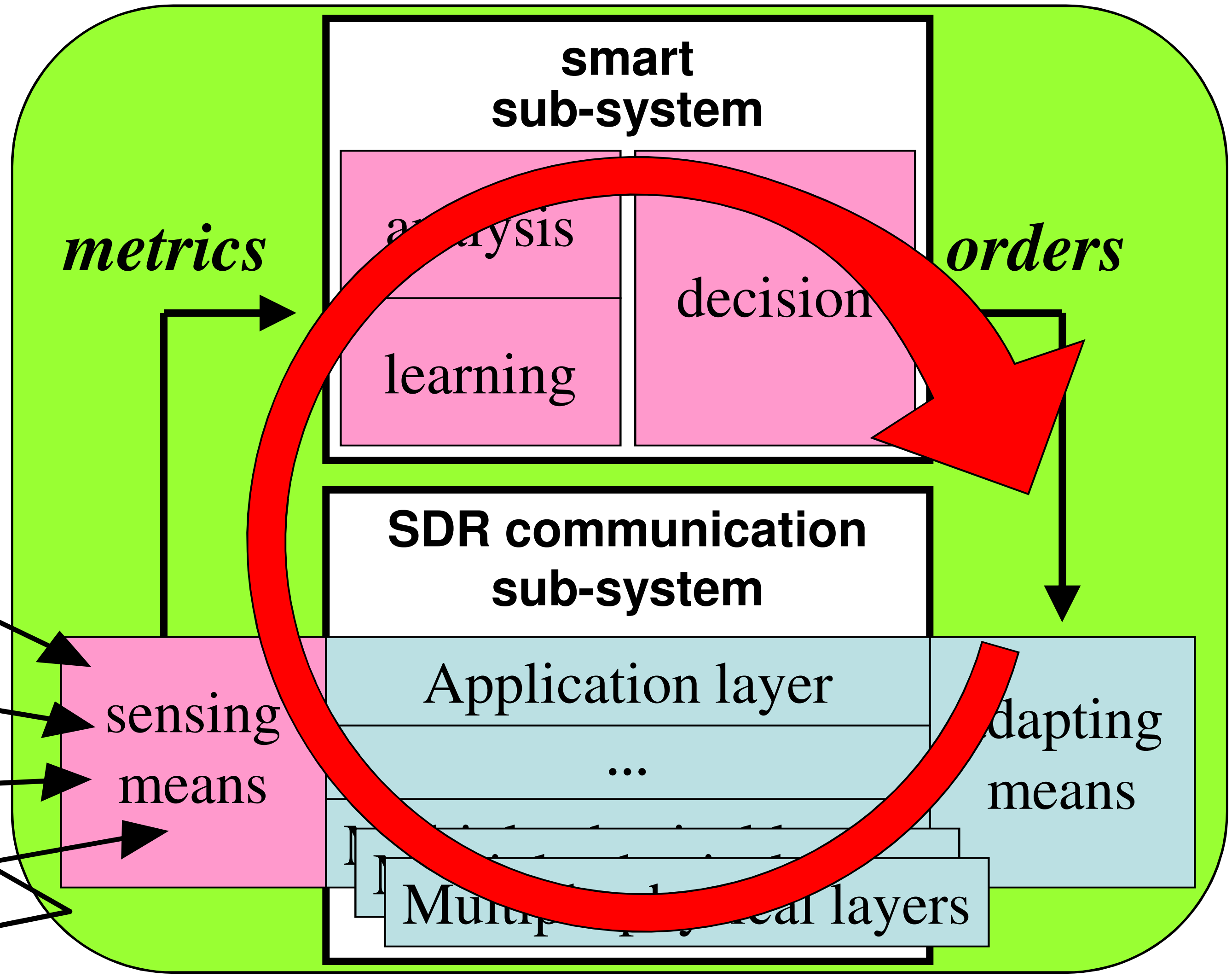


- not only spectrum oriented
- any captured information is worth
- at any layer (not only PHY layer)

Cognitive radio equipment level

- Equipment

  wide sense CR
  (spectrum & others)
  - SDR equip.
  - sensors
  - smartness



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CR context

- **Optimisation for CR:**
  - multi-critria issue
  - many parameters to be taken into account
  - possible high uncertainty on environnement

→ approximative solution may be worth

- **State-of-the-art (on configuration adaptation)**
  - genetic algorithms
  - SVM classification (Support Vector Machine)
  - fuzzy logic, neural networks, expert system

Other solutions?

- **If system behavior can be modeled by successive states and mutliple choices**
  - Markov chains (Markov Decision Process - MDP)
  - finite state machines
- **Decision trees**
- **Multi-criteria resolution**
  - agregation of criteria in one or Pareto equilibrium (set of non comparables solutions)

→ Need to combine methods in CR context

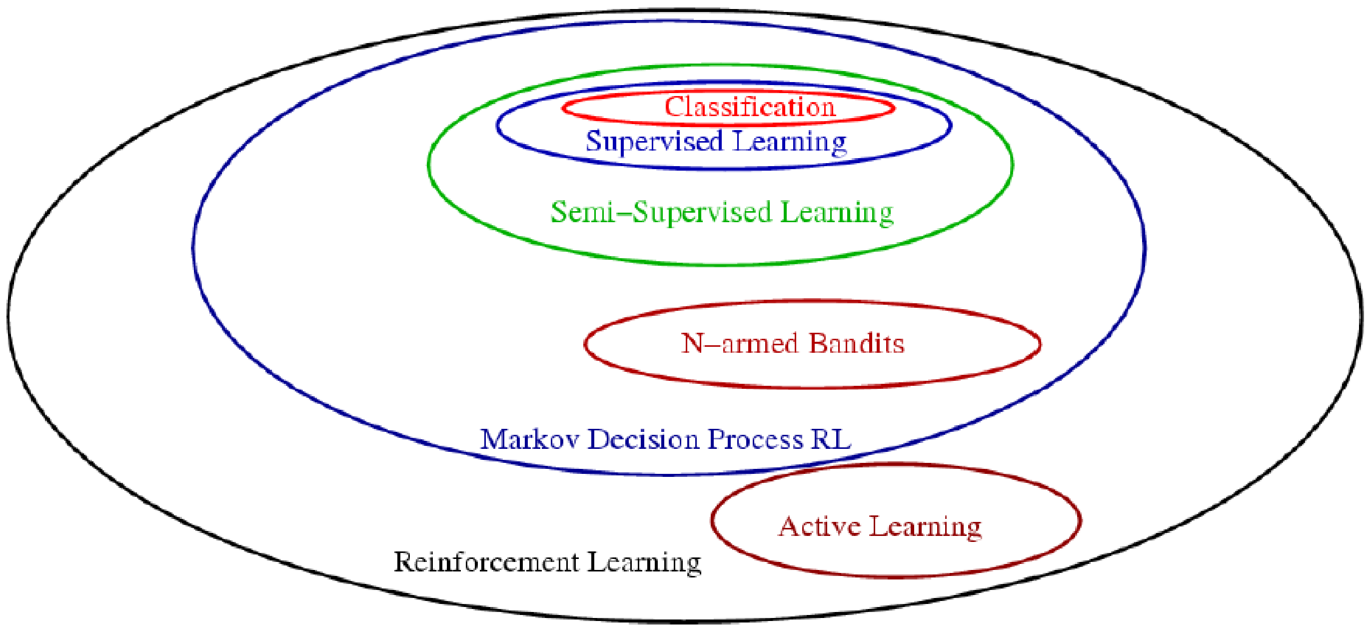
→ Also imply <u>learning</u> to alleviate uncertainty

Learning techniques

- **Principle**
  - Trials on the environment
  - Infere decision making rules
- **Examples**
  - Artificial Neural Networks (ANN)
  - Statistical learning
  - Evolving connectionist systems (ECS) (example of evolving neural networks)
  - Regression models
  - reinforcement learning (RL)

Possible hierarchy of learning methods

- From reinforcement learning community



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- Anyway, decision making for CR is hard to describe/classify ➔ hard to choose for CR

Towards a classification of decision making for CR

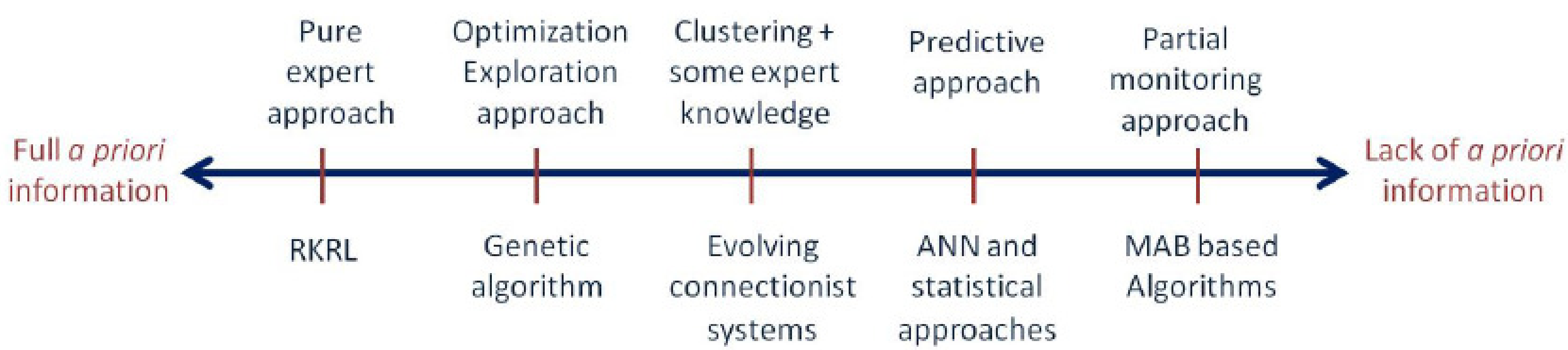
- **Dimensioning the decision making engine is submitted to 3 constraints in CR context**
  - constraints imposed by the environment
    - allocated frequency bands, tolerated interference, etc.
  - constraints related to the user's expectations
    - service: voice, video-conferencing, data, streaming, etc.
    - maximizing QoS, minimizing energy consumption, minimizing cost, maximizing spectral efficiency, etc.
  - the constraints inherent to the equipment
    - depending on the level of flexibility, the abaility to adapt
    - modulation, pulse shaping, symbol rate, transmit power, etc.
- **Depending on the "*a priori* knowledge" on these 3 constraints (information & limitation)**

Example on constraint #1

- **Constraints of the surrounding environment**
  – communication rules to respect
    - allocated frequency bands, tolerated interference, max power to transmit, radio standard, etc.

- **If no degree of freedom for the equipment**
  ➔ no possible cognitive behavior
    - obey the rigid rules (current status)
- **If no constraint imposed by the environment**
  – a CR equipment is still limited in function of its abilities and user expectations

- **Depending on the degree of *a priori* knowledge, different decision making solutions may be worth using in each case**



[1] Wassim JOUINI, Christophe MOY, Jacques PALICOT, "On decision making for dynamic configuration adaptation problem in cognitive radio equipments: a multi-armed bandit based approach," 6th Karlsruhe Workshop on Software Radios, WSR'10, Karlsruhe, Germany, March 2010

Decision making inside a CR equipment

- **Left side (high *a priori*) decision approaches have been addressed a lot in the litterature**
  - also in the CR field

[2] C.J. Rieser, "Biologically Inspired Cognitive Radio Engine Model Utilizing Distributed Genetic Algorithms for Secure and Robust Wireless Communications and Networking", PhD thesis, Virginia Tech, 2004

[3] N. Colson, A. Kountouris, A.Wautier, L. Husson, "Cognitive decision making process supervising the radio dynamic reconfiguration", CronwCom 2008

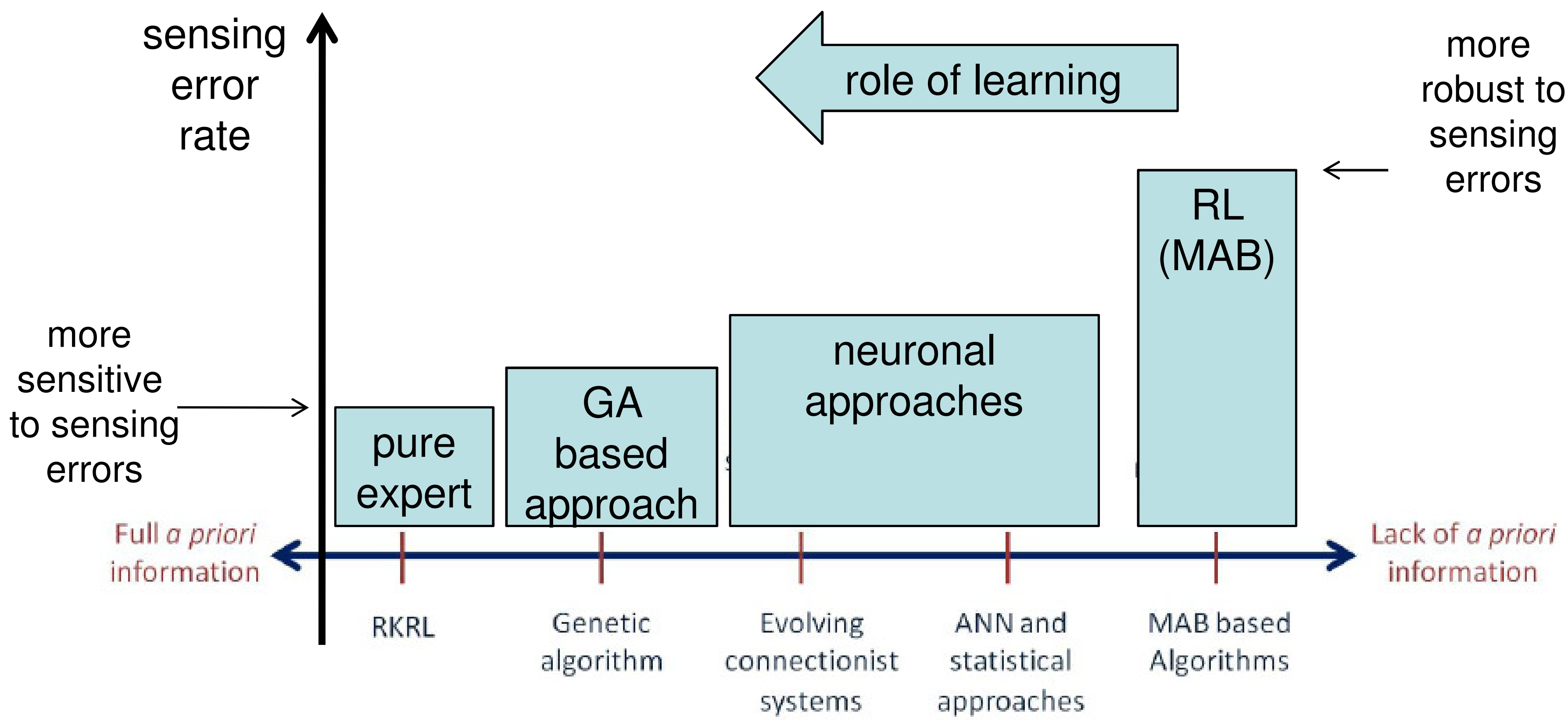
[4] N. Baldo, M. Zorzi, "Fuzzy logic for cross-layer optimization in cognitive radio networks", Consumer Communications and Networking Conference, January 2007

[5] C. Clancy, J. Hecker, E. Stuntebeck, "Applications of machine learning to cognitive radio networks", IEEE Wireless Communications Magazine, vol 14, 2007

[6] T. Weingart, D. Sicker, and D. Grunwald, "A statistical method for reconfiguration of cognitive radios", IEEE Wireless Commun. Mag.,vol. 14, no. 4, pp. 3440, August 2007

[7] T. W. Rondeau, D. Maldonado, D. Scaperoth, C.W. Bostian, "Cognitive radio formulation and implementation", IEEE Proceedings CROWNCOM, Mykonos, Greece, 2006

- **Taking into account sensing imperfections**



[8] Wassim JOUINI, Christophe MOY, Jacques PALICOT, "A decade of reasearch on decision making for cognitive radio," submitted to Journal on Wireless Communications and Networking

Decision making and CR

- **Often if not always mix techniques**
- **But we may expect that most of the time a CR equipment will have to make decisions**
  - on a high number of criteria
  - with a lot of unknwown, uncertainty
- **Hardest case: a minimum of knowledge**
- **Example of dynamic configuration adaptation (DCA) and opportunistic spectrum access (OSA)**

➔ a lot of unknown information

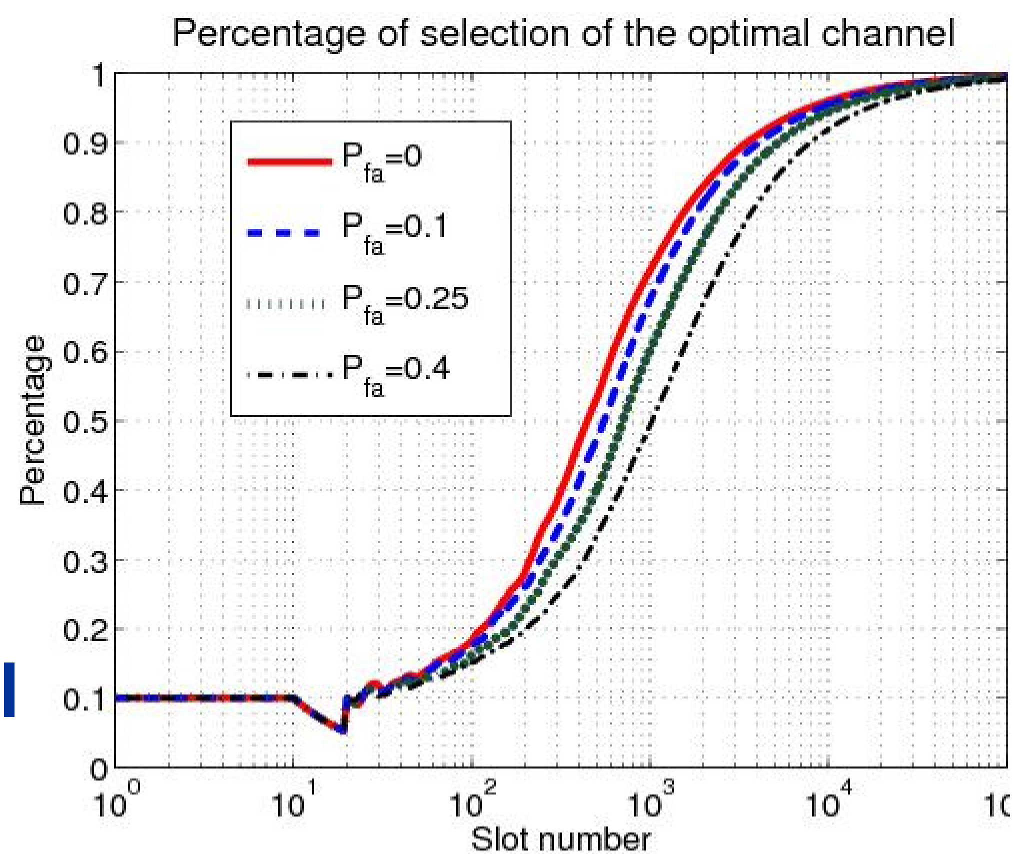
Decision making for dynamic configuration adaptation (DCA)

- **Future scenario of full-free real-time link adaptation (just impact at PHY layer studied here)**
- **Depending on**
  - the environment: propagation, network load, etc.
  - the equipment capabilities in terms of flexibility: constellation, channel coding, interleaving, etc.
  - the user: communication nature, required QoS, contract, location, speed, etc.
- **What is the best configuration?**
- **At every instants?**

Decision making for opportunistic spectrum access (OSA)

- **A secondary user (SU) may access the spectrum dedicated to a primary user (PU)**
- **Depending on**
  - the environment: bands availability, BW, etc.
  - the equipment capabilities in terms of flexibility: carrier frequency, filtering, constellation, etc.
  - the user: communication service, required QoS, location, etc.
- **What is the best channel choice?**
- **At every instants?**

- **OSA of 10 channels with different probabilities of occupation by primary users**
- **no *a priori* knowledge**
- **goal: a SU learns and converges on most available channel**
- **Percentage of time the UCB selects the optimal channel (under various sensing errors probabilities: P_{fa})**



[9] Wassim JOUINI, Christophe MOY, Jacques PALICOT, "Upper Confidence Bound Algorithm for Opportunistic Spectrum Access with Sensing Errors", CrownCom'11, 1-3 June 2011, Osaka, Japan

Terminal-centric or network-centric?

- **Network-centric**
  - concentrate smartness in the network
  - more processing power available (plug)
  - more complex computations
- **Terminal-centric**
  - distribute decision making
  - make decision where information is
  - less sensing data to transfert through the air

Need of equipment management for CR

➔ Anyway, CR equipments in both cases

➔ Certainly coexistence of both indeed

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What is a CR equipment made of?

- **A CR equipment is no more only**
  - radio signal processing
- **In addition**
  - specific signal processing for sensing
  - specific signal processing for decision making
  - some management / a SW architecture
- **Heterogeneous hardware architecture**
  - multi-processing
  - different nature: DSPs, FPGAs, ASICs

HDCRAM, what for?

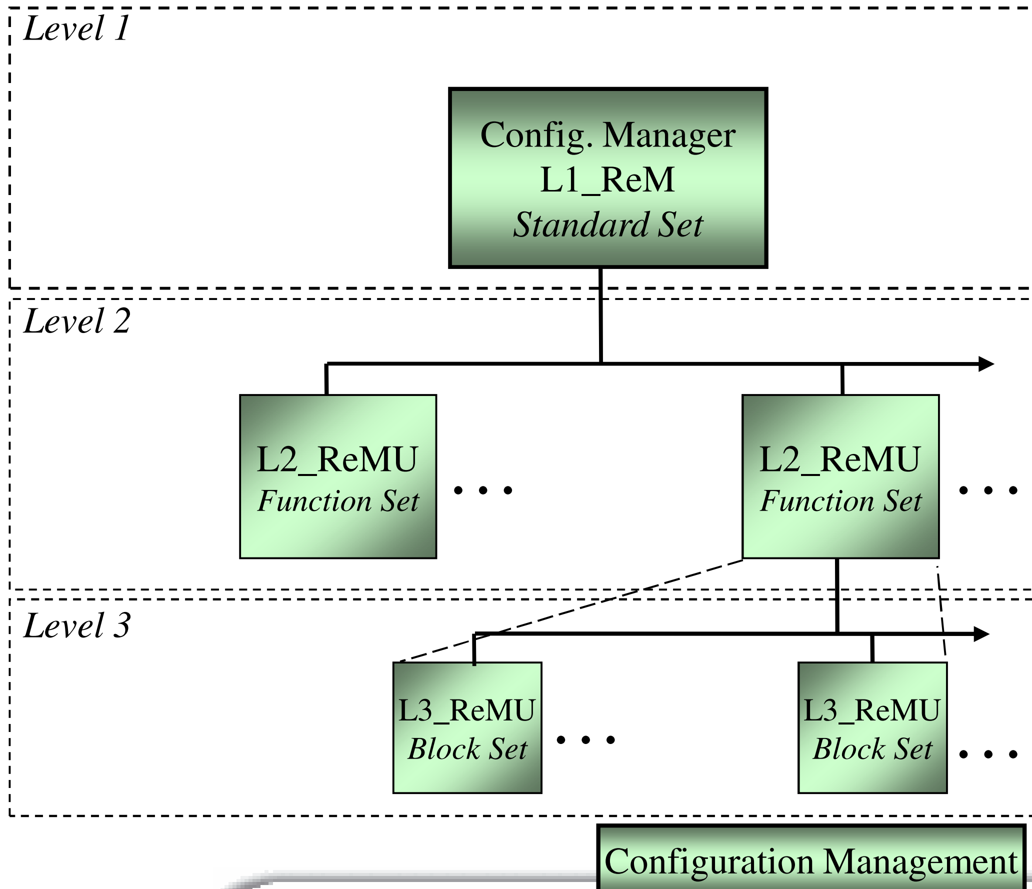
- **How to aggregate/integrate all 3 elements of cognitive cycle into a CR equipment?**
  - configuration management
  - sensing
  - decision making
- **We propose HDCRAM - Hierarchical and Distributed Cognitive Radio Architecture Management**
- **A skeleton (rules) to make all 3 work together**

[10] Christophe MOY, "High-Level Design Approach for the Specification of Cognitive Radio Equipments Management APIs", Journal of Network and System Management - Special Issue on Management Functionalities for Cognitive Wireless Networks and Systems, vol. 18, number 1, pp. 64-96, Mar. 2010

Reconfiguration management: HDReM

- **From a configuration management**
  - one L1_ReM
  - several L2_ReMUs
  - each having several L3_ReMUs

HDReM : Hierarchical and Distributed Reconfiguration Management

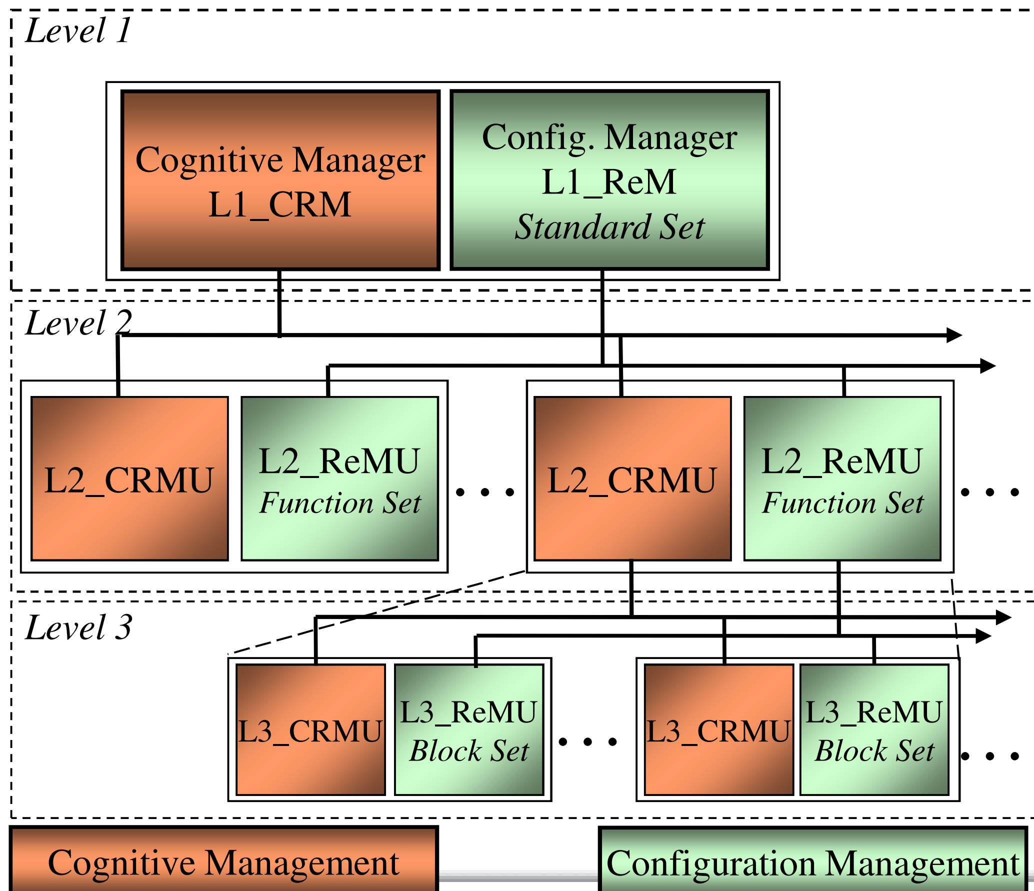


[11] Jean-Philippe DELAHAYE, "Plate-forme hétérogène reconfigurable : application à la radio logicielle", Ph.D. thesis, 2007

Cognitive Radio management: HDCRAM

- **To a CR management**
  - one L1_CR
  - several L2_CRUs
  - each having several L3_CRUs

HDCRAM : Hierarchical and Distributed Cognitive Radio Architecture Management



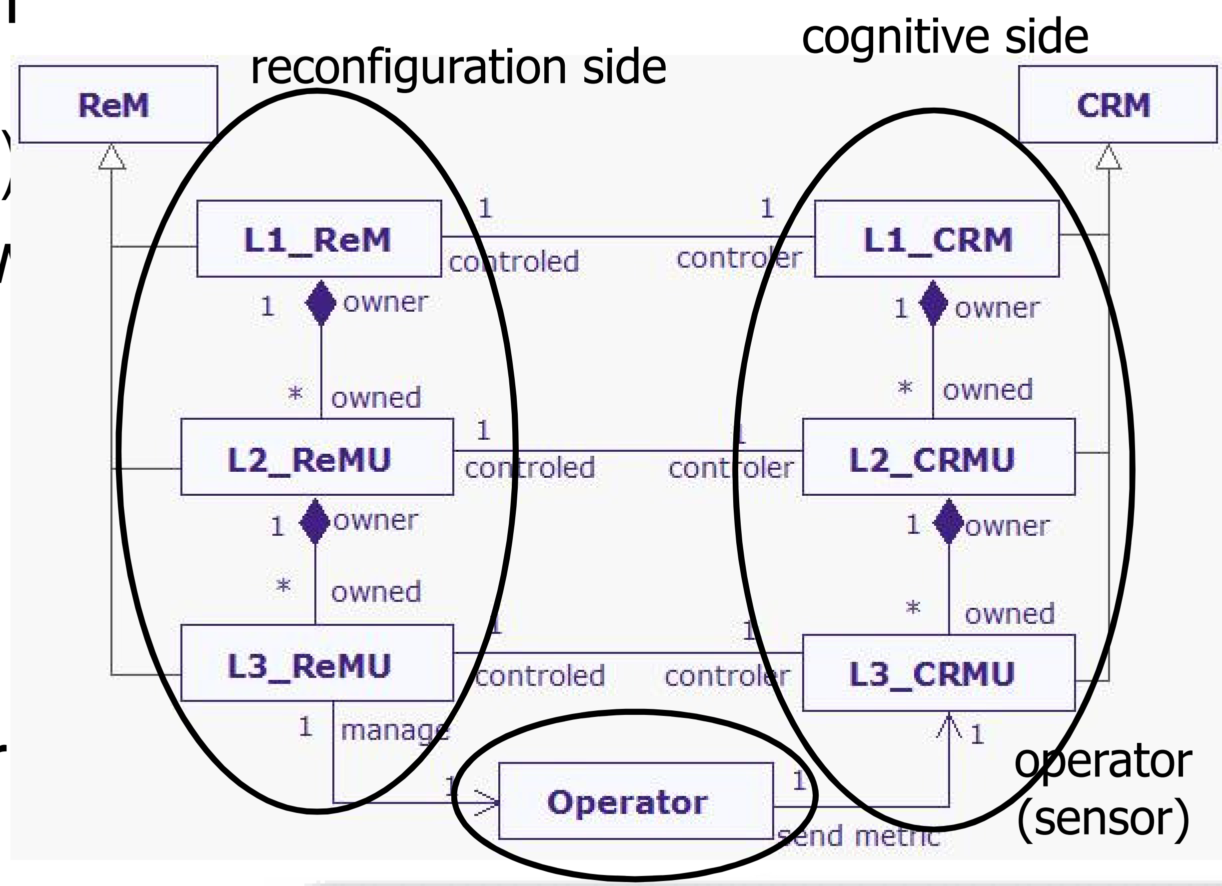
[12] Loïg GODARD, Christophe MOY, Jacques PALICOT, "From a Configuration Management to a Cognitive Radio Management of SDR Systems" ,*CrownCom'06*, 8-10 June 2006, Mykonos, Greece

HDCRAM metamodel

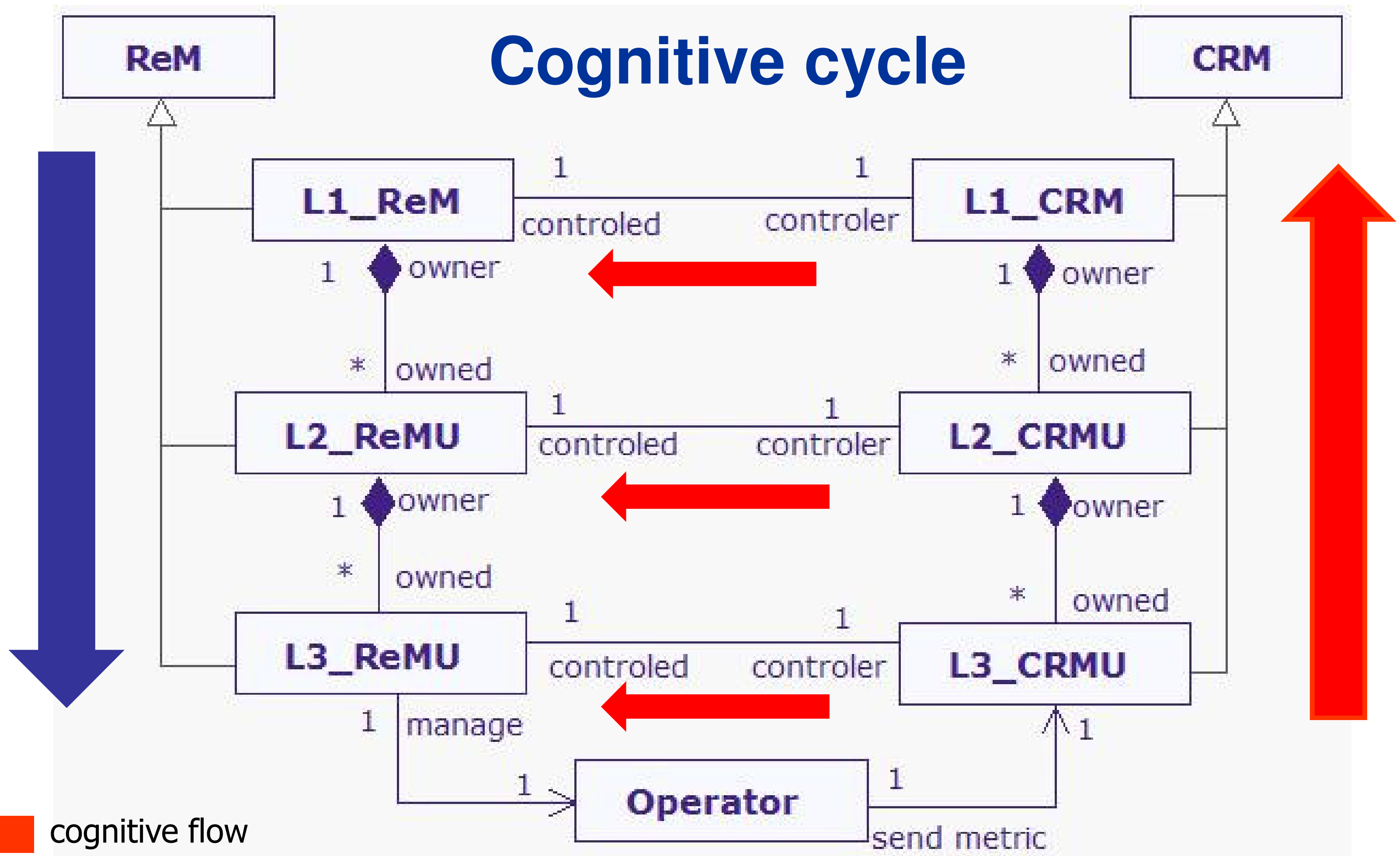
- **Formalisation of HDCRAM**
  - lists all classes / metrics / concepts
  - standardized syntax and view (UML)
- **May be re-used by anybody**
  - evaluation / comparison
  - to complete it (if necessary)
- **A CR Metamodel**
  - rules to be followed to build a CR equipment
  - some kind of language (DSL: Domain Specific Language)

[13] Loïg GODARD, Christophe MOY, Jacques PALICOT, "An Executable Meta-Model of a Hierarchical and Distributed Architecture Management for the Design of Cognitive Radio Equipments", Annals of Telecommunications, Special issue on Cognitive Radio, vol. 64, pp.463-482, number 7-8, Aug. 2009

- **HDCRAM metamodel**
  - represented in a standarded manner (UML)
  - factorized view of HDCRAM
  - has to be instanciated for each CR equipment design scenar



Information transfers through HDCRAM



cognitive flow

reconfiguration flow

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CR equipment design paradigm

- **CR equipment design is complex**
- **Need to mix**
  - signal processing (radio, sensors, application, etc.)
  - management (SW)
  - heterogeneous programing (HW/SW co-design)
  - many possible scenari

→ **Requires new design approaches**

→ **High level design**

High-level design

- **A wide variety of topics to be addressed during design, by various experts**
- **Need**
  - – abstraction
  - – exploration facilities before code generation
  - – interdisciplinary understanding
  - – optimization weekness compensated by productivity gains

➔ thanks to high-level design approach

[14] Stéphane LECOMTE, Samuel GUILLOUARD, Christophe MOY, Pierre LERAY, Philippe SOULARD, "A co-design methodology based on Model Driven Architecture for Real Time Embedded systems",Mathematical and Computer Modelling Journal, Vol. 53, Issues 3-4, pp. 471-484, Feb. 2011

HDCRAM design reference for CR management

- **HDCRAM simulator may be used at a very first stage of the design**
  - CR-oriented design thx to HDCRAM metamodel
  - simulation of design scenari
  - only functional (currently not timed for instance)
- **Industrial perspective: a design methodology based on a UML approach**
- **Compatibility between all CR equipments designed with the same rules**

In a wider design perspective: MOPCOM design flow example

- **Example of a 3 layers design approach: MOPCOM (from a collaborative research project)**
- **MDA modeling (Model Driven Architecture)**
  - PIM – Platform Independent Model
  - PSM – Platform Specific Model
  - all UML features
    - standardized views and graphs
    - documentation
    - code generation

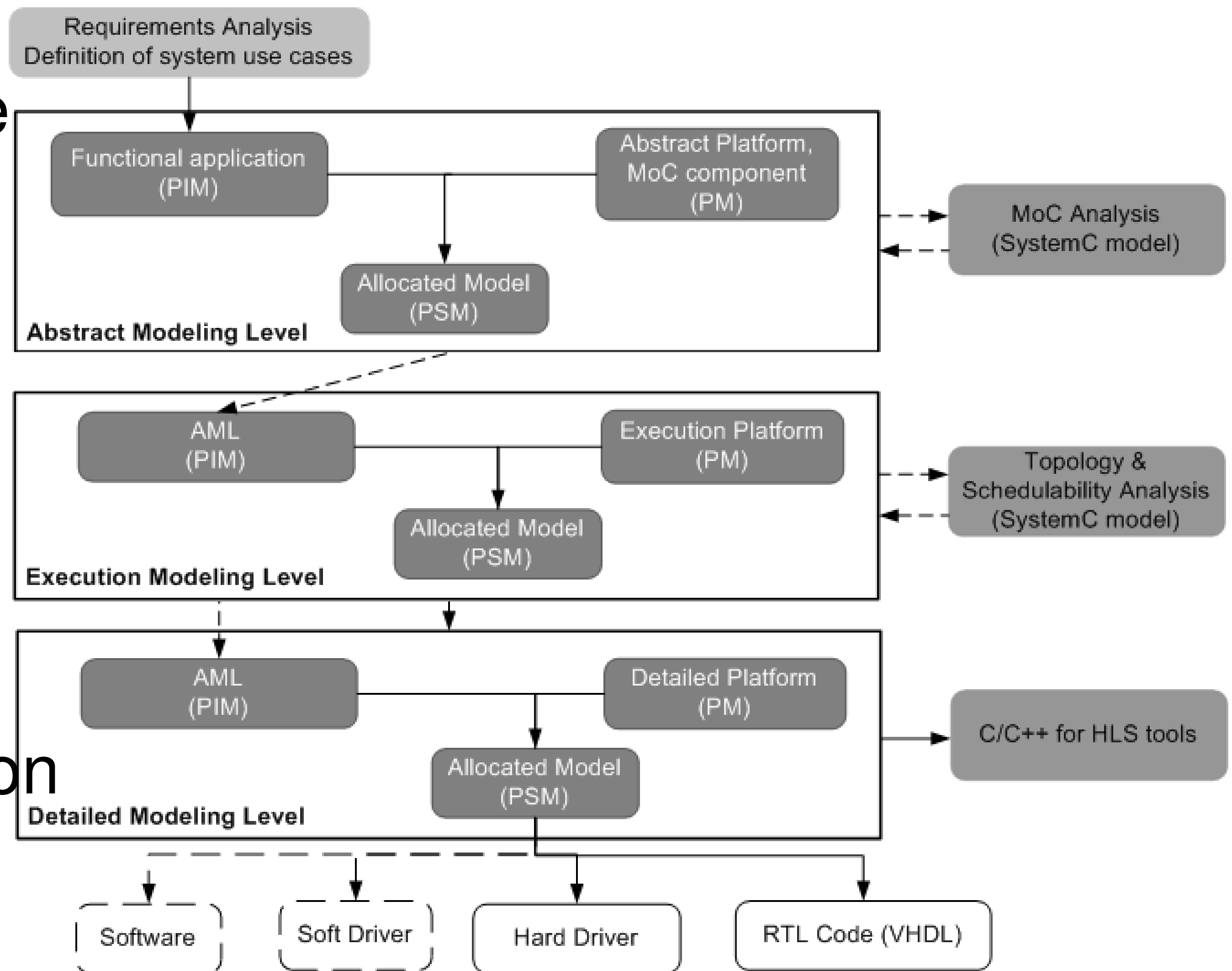
➔ let's see how derive it for CR design

MOPCOM design flow

- **From**
  - high leve specif.

Not specifically thought for CR, but for future embedded systems design

  - to code generation



Advantages for industrial development

- **Same environment from high level specification to implemented code for heterogeneous targets (DSPs, FPGAs)**

- **Common UML representation for a common understanding all over design process**
  – management
  – SW engineers
  – HW engineers
  – system engineers, integrators

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Conclusion

- **Decision making for cognitive radio**
  – the choice of decision method depends on *a priori* knowledge on the environment
- **Management architecture (HDCRAM)**
- **Introduction to high level modeling for CR**
  – a trend for complex HW/SW systems
  – including CR specificities (cognitive cycle)
  – metamodel / high-level design flow