« From Software Radio to Cognitive Radio: The Technological Challenges »

TUTORIAL AICT 2009 (24 May 2009)

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Outline

- SUPELEC / SCEE presentation
- Spectrum management
  - Current situation
  - Spectrum sharing
  - Wireless capacity
- Introduction to Cognitive Radio
  - General remarks
  - A more general « View »
  - The « Sensorial Cognitive Radio Bubble »
- The Challenges
  - Cognitive Radio Challenges
    - » The sensors
    - » The cycle management
  - Challenges related to Software Radio technology
    - » ADC
    - » Non-linearities
    - » Execution platform
- Conclusion

Outline

SUPELEC

- SUPELEC is a private engineering institute : Ecole Supérieure d'Electricité
  - electronics, energy, information technology
- created in 1894
- 3 campus in France: Paris, Rennes, Metz
- Faculty: 150
- Research scientists: 90
- 1540 engineering students (440/year)
- 230 Ph.D. students (60/year)

SCEE research team

- Located in Rennes campus
- IETR - Institute of Electronics and Telecommunication of Rennes - CNRS 6164
- SCEE research team
  - Signal, Communication and Embedded Electronics
  - head: Prof. Jacques PALICOT
  - focus: Software Radio and Cognitive Radio
  - 10 professors
  - 20 Ph.D. students
  - 2 post-docs

SCEE research axes

Software Radio and Cognitive Radio

- Digital communications and signal processing
  - non-linearities and PAPR…
  - blind MIMO demodulation, synchronisation…
- SDR and Cognitive Radio architectures
  - reconfiguration and cognitive management for heterogeneous architecture
  - SDR design (operator approach, graph optimization)
- Sensors for Cognitive Radios
  - Application layer sensors :video sensor
  - Physical layer sensors : spectrum holes detection....

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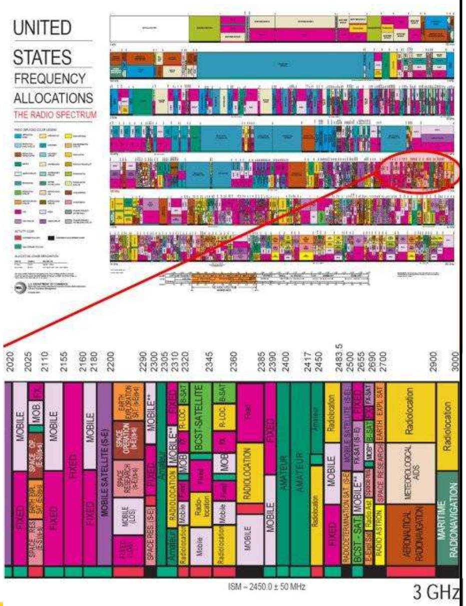
Spectrum management

Spectrum

- Natural resource
- Finite
- Public (only the usage can be private like UMTS licenses)

Current policy

- Fixed allocation
- Long time allocation
- WARC process (World Administrative Radio Conference) /5 years
- Rigid rules



Beyond 3 G = *New 4G standard
*Convergence

Two concepts for convergence

- Cooperative networks concept
  - Agreement for exchanging traffic
  - Agreement for sharing spectrum
  - Joint configuration of network segments
  - Require extensive cooperation
- Adaptive networks
  - Adapt their behavior to the environment
  - Overcome the above shortcomings

Working Group 6 White Paper, "Cognitive Radio and Management of Spectrum and Radio Resources in Reconfigurable Networks",WWRF, 2005
I. F. Akyildiz, S. Mohanty, J. Xie, "A ubiquitous communication architecture for next-generation heterogeneous wireless systems", *IEEE Commun. Mag.*, Vol. 43, No. 6, June 2005, pp. s29-s36.
P.Demestichas, G.Vivier, K.El-Khazen, M.Theologou, "Evolution in wireless systems management concepts: from composite radio to reconfigurability", *IEEE Commun. Mag.*, Vol. 42, No. 5, May 2004, pp. 90-98
End to End Reconfigurability (E2R), IST-2003-507995 E2R, http://www.e2r.motlabs.com

Spectrum management control model

- Centralized
  - Management of spectrum opportunities is controlled by a single entity.
  - The spectrum broker
  - Real time spectrum market.
- Distributed
  - The interaction is "peer to peer" model
  - Radio "nodes" are collectively responsible

Remark: this notion will be also valid for cognitive radio management principle

Spectrum management

Radio Spectrum Regulation

- Licensed spectrum for exclusive usage
  - Exclusive access to spectrum.
  - Usage bought by operators (UMTS).
  - Restricted to a specific RAT.
  - Check by regulatory bodies.
- Licensed spectrum for shared usage
  - Primary and secondary users
  - Restricted to a specific RAT
- Unlicensed spectrum
  - Access allowed, respect to some minimal rules
- Open spectrum

FCC model

exclusive use model

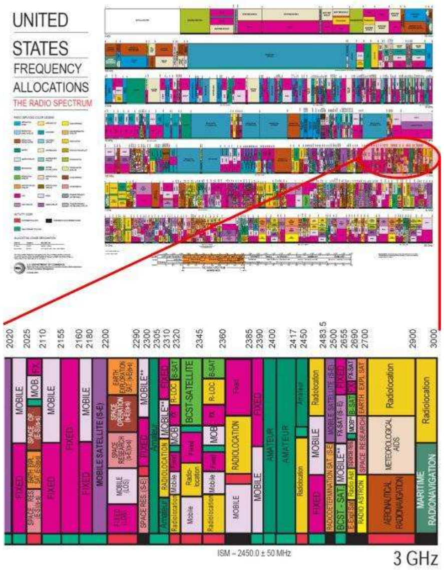
Command and control

Open access

Spectrum management

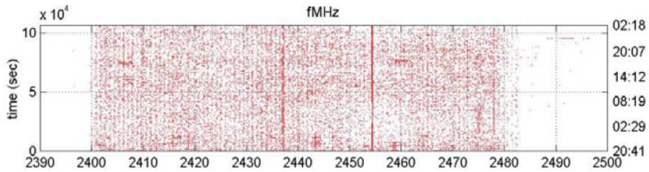
Integration:

- in time
- in space
- in service

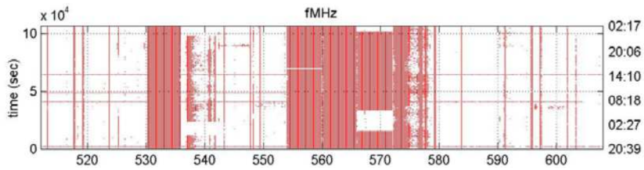


No available spectrum (scarce resource)

BUT



2,4 GHz band occupancy 01/September/2004 in New York



TV band occupancy 01/September/2004 in New York

Hic et nunc

(Here and now)

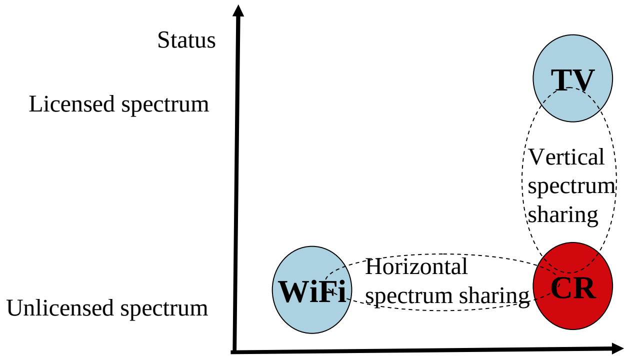
Free spectrum

Spectrum sharing

- **Dynamic spectrum access**
  - **Vertical and Horizontal sharing**
  - **Underlay sharing**
  - **Overlay sharing**
  - **Opportunistic communications**

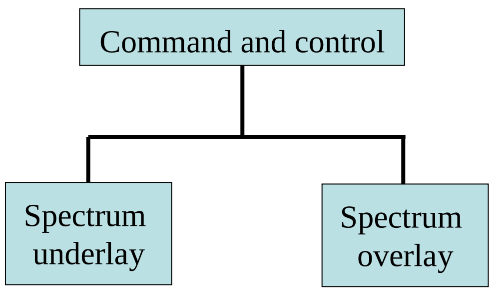
Q Zhao, A Swami, “A survey of Dynamic spectrum access SP and networking perspectives, ICASSP 2007

Dynamic spectrum access
Vertical and Horizontal sharing (from [1])

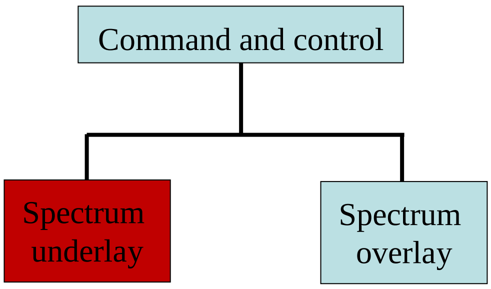


[1] Working Group 6 White Paper, “Cognitive Radio and Management of Spectrum and Radio Resources in Reconfigurable Networks”,WWRF, 2005 J. Kruys, "Co-existence of Dissimilar Wireless Systems," http://www.wifi.org/opensection/pdf/coexistence_dissimilar_systems.pdf, July 2003

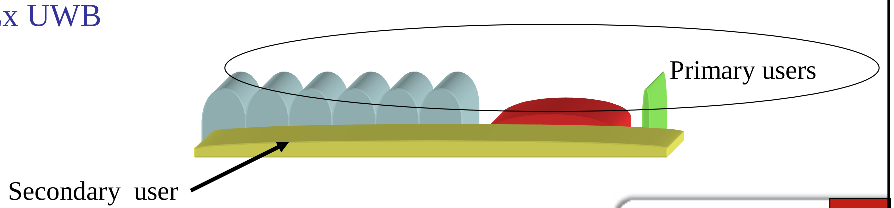
Dynamic spectrum access



Dynamic spectrum access

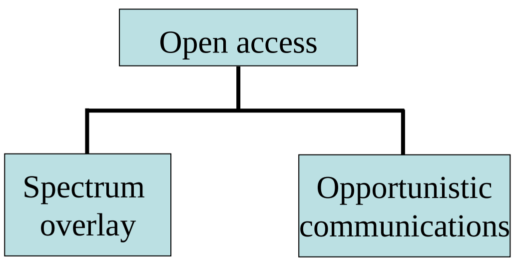


- Spread the signal
- Power below a threshold for the primary user
- Interference temperature concept
- Ex UWB



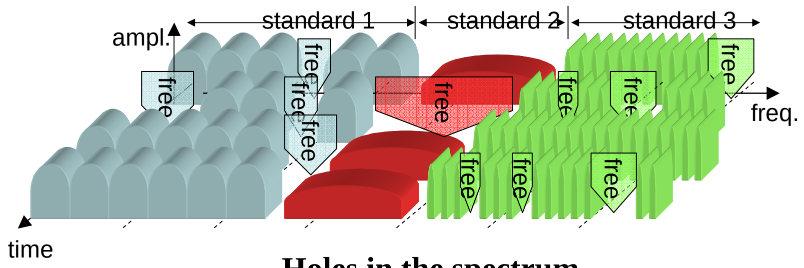
Dynamic spectrum access

Spectrum opportunity
=
White spectrum
=
Spectrum Hole



Same notion = different words in the literature

Spectrum opportunities identification = great challenge



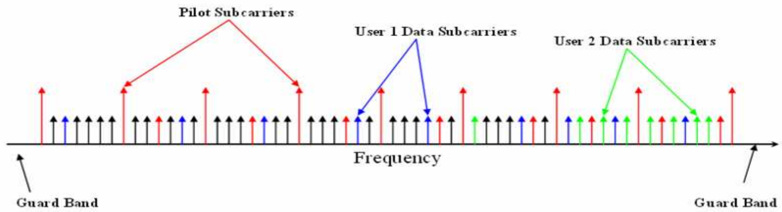
Holes in the spectrum

- **Need to detect them (Filtering and detection)**
- **Agreement between TX and Rx**
- **Then need**
  - **to characterize the hole (noise level, interference level,...).**
  - **To identify the impulse response between the Rx and the Tx in this hole.**

Discussed later in the physical layer sensor

Spectrum pooling with OFDM [1]

- Ideal modulation example for CR
  - Huge literature on spectrum allocation
  - Study of the best allocation to optimize the capacity.
  - Easy to switch on and off some carriers depending on the primary and secondary user
  - Take care of the spectrum insertion (new waveform for PSD purposes)



[1] T. Weiss and F. Jondral, "Spectrum pooling: An innovative strategy for the enhancement of spectrum efficiency," *IEEE Communications Magazine*, pp. S8-S14, 2004.
.

Spectrum management

- Great Challenge….
- Manage spectrum like a chess game:
  - Several thousands channels instead of 64 squares.
  - Several tens ... ndreds) potential signals occupying ... d of 32 game items
  - ... ording to ... r parameters

Need of Cognitive Radio

Outline

Cognitive Radio - Introduction

- Introduced by J.Mitola in 1999
- Conceptualization and « theorization » of ideas and concepts fashionable in the world of Radio communications
  - Environmental adaptation in a broad acceptation
  - Intelligence in the network and terminal
  - Terminal independence towards network and operator
  - User independence towards technique
- Is based on a truly Software Radio Technology

Cognitive Radio - Introduction

Goods surface transport analogy (1/3)

- Rail transport is a natural link between two stations:
  - The train used to transport the good must follow the rails and cannot choose any other "routes", nor any other time schedule.
  - Our analogy consists in saying that a conventional radio communication using a GSM type standardized link does not offer any possibility other than following the rails (for a given frequency and modulation), so that the information reaches its addressee.

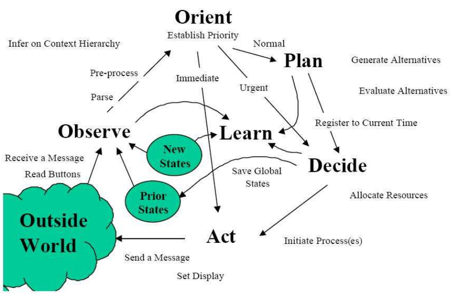
Goods surface transport analogy (2/3)

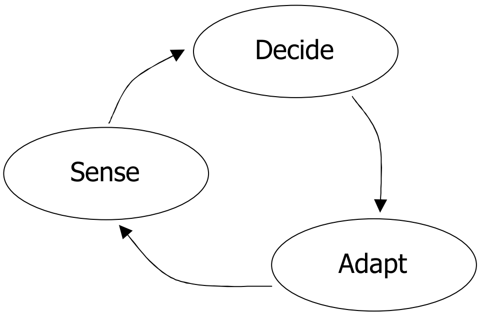
- When this good is conveyed by road,
  - the existing infrastructure enables to connect these 2 locations freely as for time schedule, and journey.
  - Let's pursue our analogy, the software radio will be, for us, an infrastructure equivalent to the road network, which will offer a choice (frequency, modulation...) in order to transmit information from the transmitter to the recipient.

Goods surface transport analogy (3/3)

- When this good is conveyed by road,
  - the driver will be able to choose freely his journey, on the road network, according to several criteria (travel time, distance, toll costs, anticipated traffic, departure time, etc...).
  - Equally, Cognitive Radio will allow the terminal (the driver) to move in the radio infrastructure (thanks to the software radio technology), having a wider choice at its disposal, thanks to the information given by the sensors.

- Cognitive cycle of Joe MITOLA





- At its broadest sense
  - not only spectrum-oriented (our « view »)
  - all sensing means

- Studies in progress in Europe:
  - WWRF, a work group deals with « Distribution of Intelligence and Processing Capabilities » in a Software Radio context
  - E²R : End-to-End Reconfigurability
  - ORACLE : Opportunistic Radio Communications in Unlicensed Environments
  - Academic community; the main European universities working in this field are:
    - » Karlsruhe University
    - » Surrey University
    - » Athena University (NTUA)
    - » UPC - Barcelona
- In France:
  - SUPELEC – Rennes
  - SUPELEC/Alcatel-Lucent Chair on Flexible Radio (Mérouane Debbah)
  - EURECOM
  - Recently, Signal Processing laboratories (« Link Adaptation » aspect)

Cognitive Radio - Introduction

• **Journal special issues (very good indicator):**

- Special Issue on Cognitive Radio : Theory and Applications, Journal on Selected Areas in Communications, call for papers closed on the 1st of March 2007
- Special Issue on Cognitive Radio and Dynamic Spectrum Sharing Systems, Eurasip Journal on Wireless Communications and Networking, call for papers closed on the 1st of June 2007
- Special Issue on Cognitive Spectrum Access, IET Communications : call for papers on the 30th of September 2007
- A special issue of the French telecommunication annals review is to be published: call for papers closed on the 1st of June 2008 and publication in 2009.

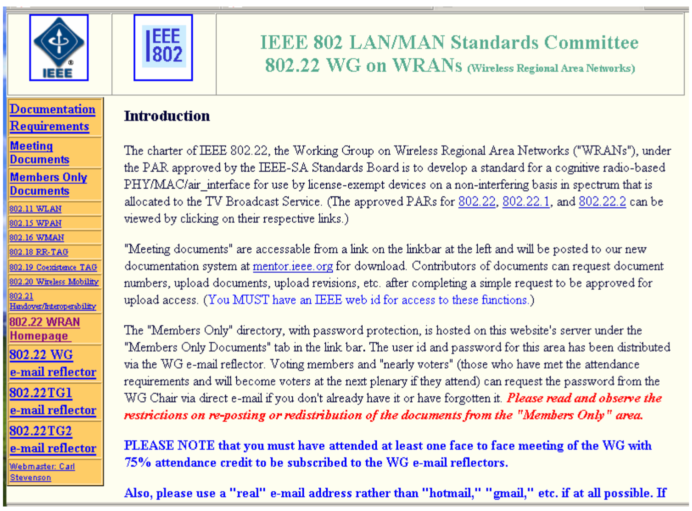
- Special Issue on Signal Processing for Software Defined Radio Handsets, Journal of Signal Processing Systems.
- Special Issue of Computer Communications on Cognitive Radio and Dynamic Spectrum Sharing Systems http://www.elsevier.com/locate/comcom.
- Software-Defined Radio and Broadcasting ;http://www.hindawi.com/journals/ijdmb/si/sdrb.html
- Many others until end 2008 but fnished in 2009

Conferences and specific events:

CROWCOM (4th edition Hannover in June 09)
DYSPAN
Dedicated sessions in many conferences

Cognitive Radio - Introduction

Standardisation: IEEE 802.22


IEEE 802 LAN/MAN Standards Committee
802.22 WG on WRANs (Wireless Regional Area Networks)

Documentation Requirements
Meeting Documents
Members Only Documents
802.11 WLAN
802.15 WPAN
802.16 WMAN
802.18 RR-TAG
802.19 Coexistence TAG
802.20 Wireless Mobility
802.21 Handover/Interoperability
802.22 WRAN Homepage
802.22 WG e-mail reflector
802.22TG1 e-mail reflector
802.22TG2 e-mail reflector
Webmaster: Carl Stevenson

Introduction

The charter of IEEE 802.22, the Working Group on Wireless Regional Area Networks ("WRANs"), under the PAR approved by the IEEE-SA Standards Board is to develop a standard for a cognitive radio-based PHY/MAC/air_interface for use by license-exempt devices on a non-interfering basis in spectrum that is allocated to the TV Broadcast Service. (The approved PARs for 802.22, 802.22.1, and 802.22.2 can be viewed by clicking on their respective links.)

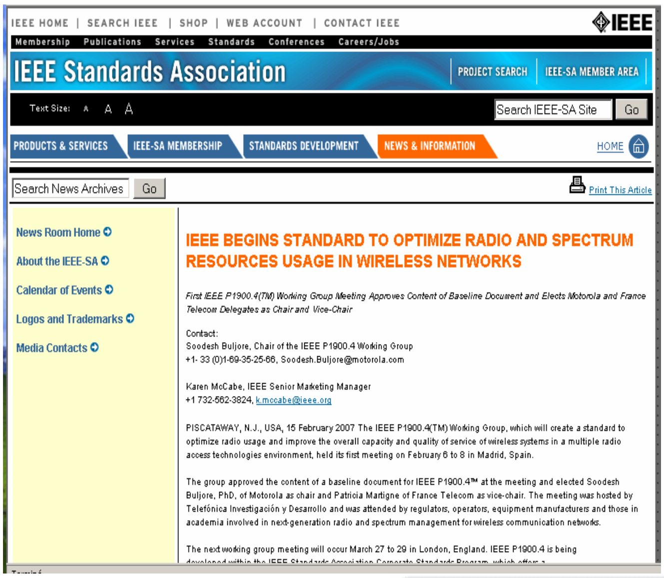
"Meeting documents" are accessable from a link on the linkbar at the left and will be posted to our new documentation system at mentor.ieee.org for download. Contributors of documents can request document numbers, upload documents, upload revisions, etc. after completing a simple request to be approved for upload access. (You MUST have an IEEE web id for access to these functions.)

The "Members Only" directory, with password protection, is hosted on this website's server under the "Members Only Documents" tab in the link bar. The user id and password for this area has been distributed via the WG e-mail reflector. Voting members and "nearly voters" (those who have met the attendance requirements and will become voters at the next plenary if they attend) can request the password from the WG Chair via direct e-mail if you don't already have it or have forgotten it. *Please read and observe the restrictions on re-posting or redistribution of the documents from the "Members Only" area.*

PLEASE NOTE that you must have attended at least one face to face meeting of the WG with 75% attendance credit to be subscribed to the WG e-mail reflectors.

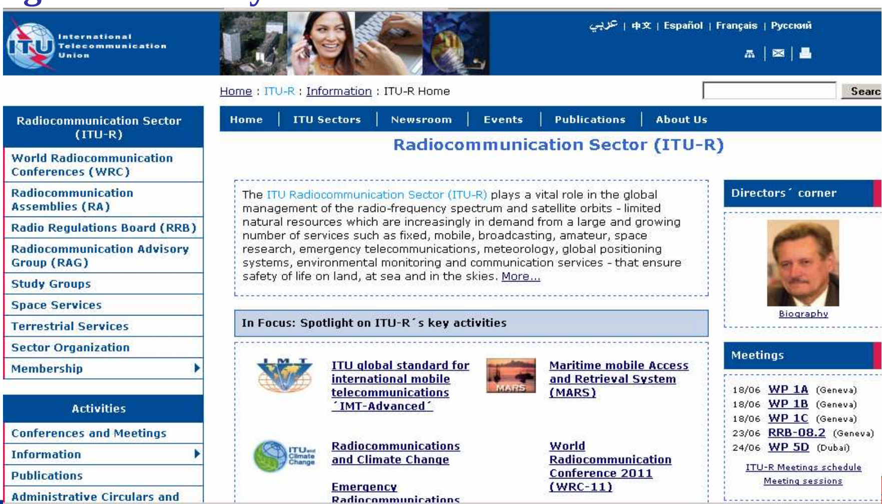
Also, please use a "real" e-mail address rather than "hotmail," "gmail," etc. if at all possible. If

Standardisation: P1900.4



IUT-R8A New ITU-R Question on

"Cognitive radio systems in the mobile service"



Standardisation : ETSI RRS TC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News Release - 30th May 2008

Future is bright for ETSI Reconfigurable Radio Systems Technical Committee ahead of Meeting #2

ETSI Headquarters, Sophia Antipolis, France - 30 May 2008

ETSI is pleased to announce the **second meeting of ETSI Technical Committee TC RRS at its Headquarters in Sophia Antipolis, 2 – 4 June 2008.**

Whereas meeting #1 agreed that future focus would be given to System Aspects, Equipment Architecture, Functional Architecture and Cognitive Pilot Channel and Public Safety, meeting #2 will focus on creating Work Items on several proposals received and on the internal Working Groups (WGs) structure to perform the

Standardisation : ETSI RRS TC ChairmanWG2 Markus Muck Infineon -Munich

Standards Landscape – ETSI RRS

Infineon

- **ETSI RRS (Reconfigurable Radio Systems)** targets the standardization of SDR and CR related technologies complementary to existing efforts.
- Motivation: SDR and CR is seen as a key technology for future wireless radio systems.
- The group has been kicked-off on 19-March-2008 with first meeting in Sophia Antipolis, France
- Current Organization:
  - WG1: System Aspects
  - WG2: Reconfigurable Radio Equipment Architecture
  - WG3: Functional Architecture & Cognitive Pilot Channel
  - WG4: Public Safety
- WG2 will meet on 26-27-August-2008 in Munich, Germany
- Information on last meetings on ETSI site:
  http://webapp.etsi.org/meetingCalendar/MeetingDetails.asp?mid=11805

SDR Forum

"Two approaches"

- There is a heavy discussion in the community to consider if most of the intelligence should be contained in the network or in the terminal
- Network-centric cognitive approach:
  - this permits to lower the terminal complexity, which is of major importance due to their restricted embedded capabilities
  - The network is also seen as the best place to centralize a very large set of information which permits global network optimization
- Terminal-centric cognitive approach:
  - the terminal itself is the best equipment to know what its operating conditions are
  - it can also benefit from network information through communication means, a distributed cognitive approach is preferred
- We believe that a combination of both is worth. Depending on each situation, one orientation may be privileged from time to time

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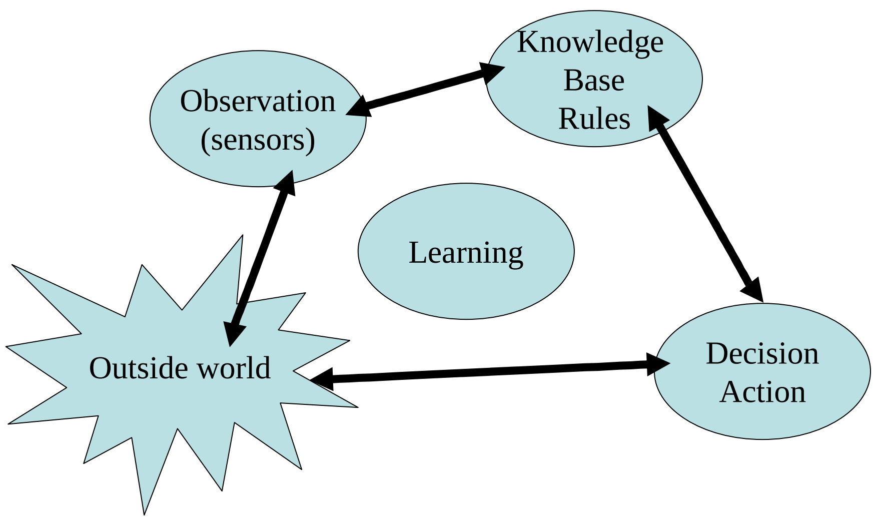
Cognitive Radio - Introduction

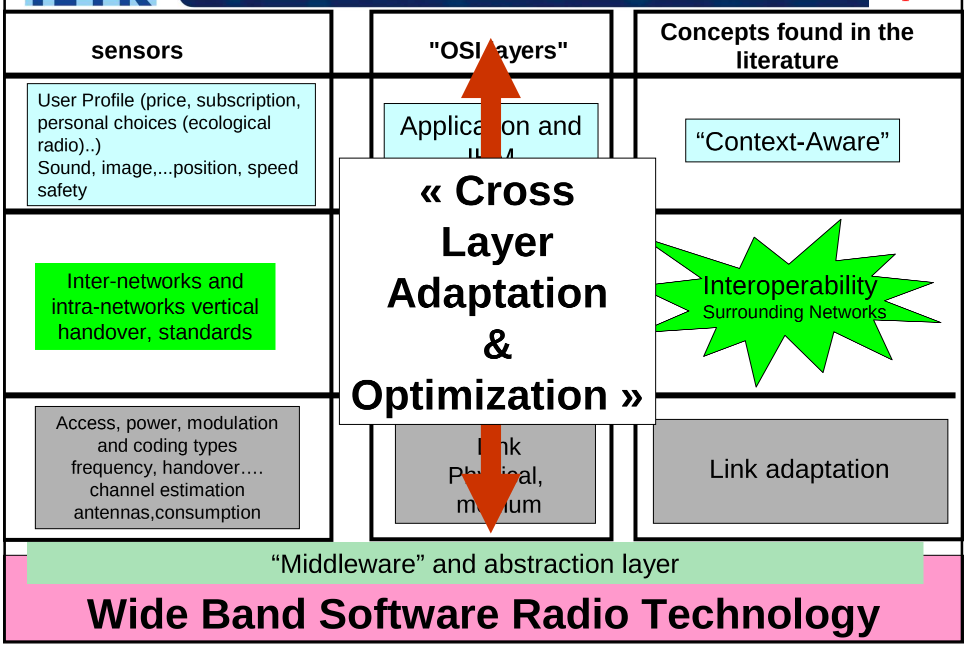
Conventional cognitive cycle



Cognitive Radio - Introduction

- A few definitions found in the literature:
  - *”Cognitive radio increases the awareness that computational entities in radio have their locations, users, networks, and the larger environment”.*
  - *« Cognition tasks that might be performed range in difficulty from the goal driven choice of RF band, air interface, or protocol to higher level tasks of planning, learning, and evolving new protocols. »*
  - *“this type of learning technique makes the Software Radio trainable in a broad sense instead of just re-configurable”*
- Broader than the conventional view limited to the spectrum optimization

A more general view of CR

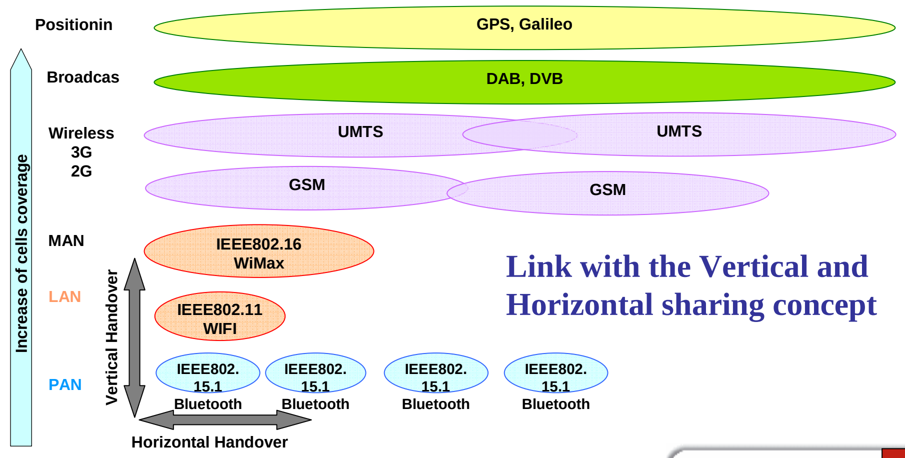


Cognitive Radio - Introduction

•"Generalized Handover" concept:

– Geographic mobility : Conventional « **Horizontal Handover** »

– Mobility between Networks, Standards, Services :« **Vertical Handover** »



Cognitive Radio - Introduction

• Decentralized view associated with a local optimization of needs and resources versus a centralized view based on the worst case scenario needs.

- Ex1 : ADC requirement due to near/Far effect
- Ex 2 : implementation of an equalizer independently of the channel IR

« Sensorial Cognitive Radio Bubble »

IETR — Supélec

- The SRB is a multi-dimensional space around CR equipment, with one dimension for each sensing capability. Each dimension (sensor) can be represented by several parameters (such as temperature and time for a thermometer).

- Our context; Double mobility
  - Spatial mobility : Horizontal handover
  - Spectral mobility: Vertical handover

- Double map
  - A conventional spatial map
  - A spectral map

- Double Analogy
  - The first one is the "human bubble"
  - The second one is the "vehicle driver bubble"

Hachemani R, Palicot J, Moy C, *The "Sensorial Radio Bubble" for Cognitive Radio Terminals*, URSI 08, The XXIX General Assembly of the International Union of Radio Science, Chicago (USA), August 2008

« Sensorial Cognitive Radio Bubble »

IETR — Supélec

First analogy: the "human bubble"

- It is the well known "bubble" in psychology and physiology. Idea of "safety bubble".
- This idea or notion is obtained thanks to our 5 senses (smell, hearing, touch, eyesight, taste).
- Human being learning through its senses .
- a 6th sense : the electromagnetic sense ?
- the "SRI bubble" will learn with this 6th sense.
- In this bubble, information is provided by all kinds of sensors analysing electromagnetic waves.

Second analogy: the "vehicle driver bubble“

- The driver knows (usually) everything inside his/her bubble.
- All this information is given by his/her 5 senses and by:
  - road markings means, other vehicles and road infrastructure emitted signals,
  - universal rules associated with driving and applying to every drivers,
  - the driving experience, associated to previously occurred situations, and which enables him/her to predict and anticipate dangers.
- The aim of a driver is to travel from a departure point to a destination without any accident under certain constraints (cost, time, number of kilometers,...), thanks to his/her "bubble"
- Similarly, the aim of a CR terminal is to send its information to the appropriate addressee without any accident (good QoS,..) under certain constraints (rate, duration, price,..), thanks to its "bubble"

The "bubble" sensors

Detectors	Layers
User Profile (price, operator, personal choices, sound, image, position, speed, safety,…	Application and man-machine Interface
Vertical inter and intra network “Handover” and standards, link burden, standards recognition,..	Transport, Network
Type of access, modulation, channel coding, carrying frequency, symbol, channel estimation, antennas lobes, available material resources, …	Network Physical

sensors classification according to the simplified layers model

Jacques Palicot ,Christophe Moy, Rachid Hachemani « Multilayer sensors for the Sensorial Radio Bubble », Physical Communication 2 (2009) pp151-165.

The "bubble" sensors

- **electromagnetic environment:** spectrum occupancy, Signal to Noise Ratio (SNR), multi-path propagation…
- **hardware environment:** battery level, power consumption, number of used gates,…
- **network environment:** telecommunication standards (GSM, UMTS, WiFi, etc.), operators and services available in the vicinity, traffic load on a link…
- **user-related environment:** localization, speed, time of day; user preferences, user profile (access rights, contract…), video and audio sensor (presence detection, face, voice recognition)…

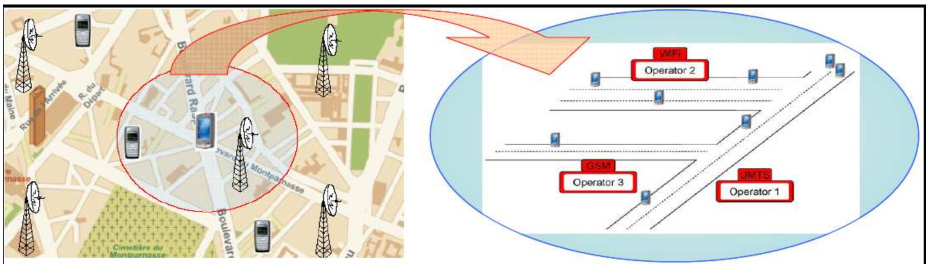
sensors classification according to the environment

The maps

- **The spatial map:**
  - **set of pertinent information that is reported in a geographical map.**
  - **These parameters can be, for example, the position of hotspots or access points, position of others terminals, etc.**
- **The spectrum map:**
  - **identifies and represents different spectrum parameters existing in the radio bubble**
  - **vary with the movement of the bubble,**
  - **Parameters using signal processing techniques :**
    - » **the carrier frequency,**
    - » **the free channels**
    - » **the telecommunication systems inside the bubble.**
    - » …
  - **Draw a map with some rules**
  - **in respect to a specific dimension (a sensor)**

The maps

- In respect to a specific dimension (a sensor).
- Figure (a) presents the projection of for example the Direction Of Arrival sensor (spatial map)
- Figure (b) presents the projection of the Standard Recognition Sensor (spectrum map)



(a) Spatial Map (b) Spectrum Map

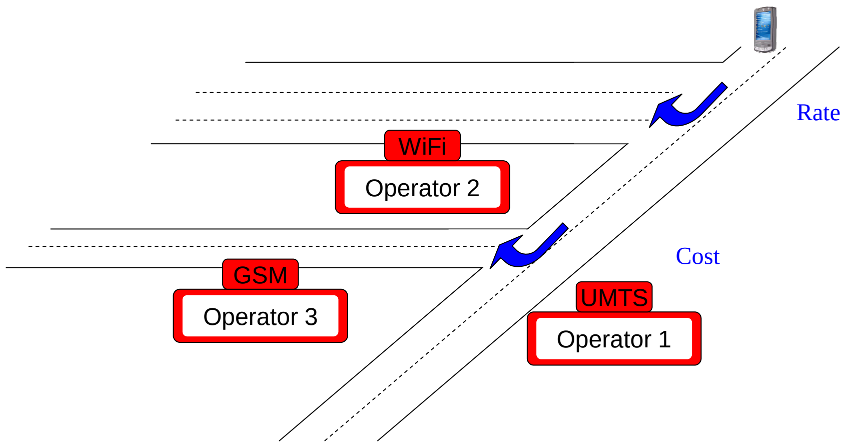
Road map	Spectrum map
Car driver	Bubble manager
Vehicle	Terminal
Road type	Standard type
Road width	Standard Throughput
Road name	Operator
One way road	Diffusion
Vehicle speed	Terminal bit rate
Branch off (change road type)	Vehicle "handover"
Branch off on the same road type	Change operator for the same standard
Forbidden road	Forbidden bandwidth
Police	Regulation body
Private way	Reserved Bandwidth
Speed limit	Limited granted rate
Give a way to any traffic coming from the right	standard Priority access
Traffic jam	Overburdened radio link

Spectrum map

- Rules examples for spectral map construction
- **The spectrum map is evolving with the moving of the terminal in the spatial map**

• Similar approach (road analogy) proposed at the same time by Virginia Tech (Reed) and by SUPELEC/SCEE.

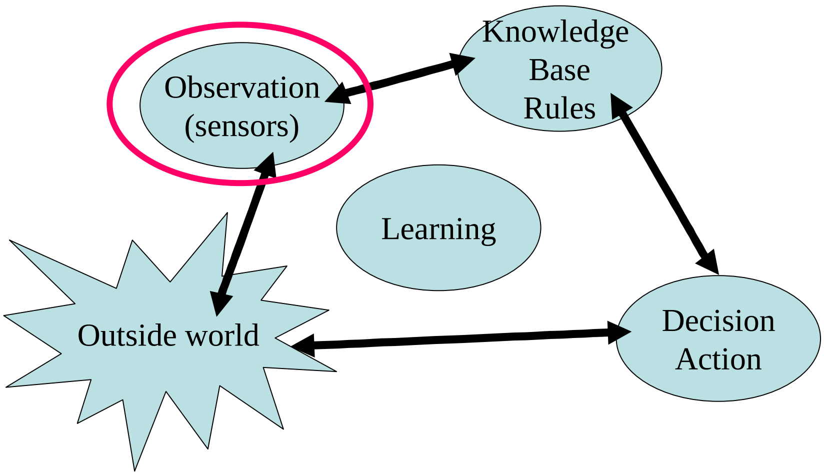
« Sensorial Cognitive Radio Bubble »



Outline

Cognitive Cycle Challenges

Conventional cognitive cycle

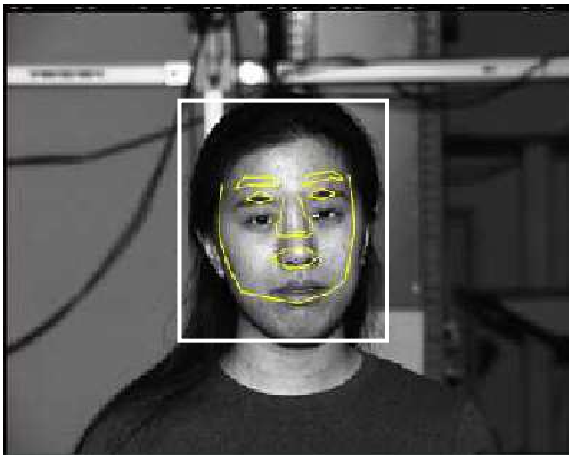


Application layer sensors

Objectives

- Application layer sensors ("Context Aware"):
- Identify, analyse and interact with the user (audio, video, other,...)
- Effects on radio access
  - Video sensor
  - Obstacle: Unknown face characteristic points precise positioning, in real conditions.
  - Solution obtained thanks to the Appearance Active Models.

Face Detection Sensor



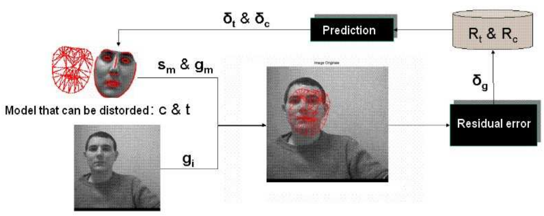
face characteristic points precise positioning:2DAAM

1. **Face statistical modelling**

   AAM : Learning phase

2. **Model distortion in order to lay on the unknown face**

AAM : Segmentation.



S. Le Gallou, G. Breton, C. Garcia**, R. Séguier**, *Distance Maps: a robust illumination preprocessing for active appearence models*, International Conference on Computer Vision Theory and Applications (VISAPP) Setubal, Portugal, February 2006

face characteristic points precise positioning: 2DAAM

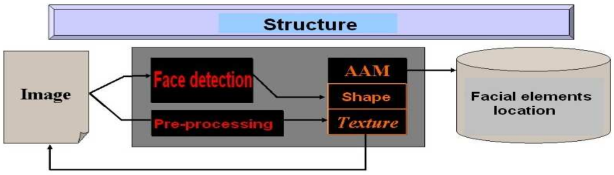
AAM: Disadvantages

Initialization (need of an initialization close to the optimal solution)

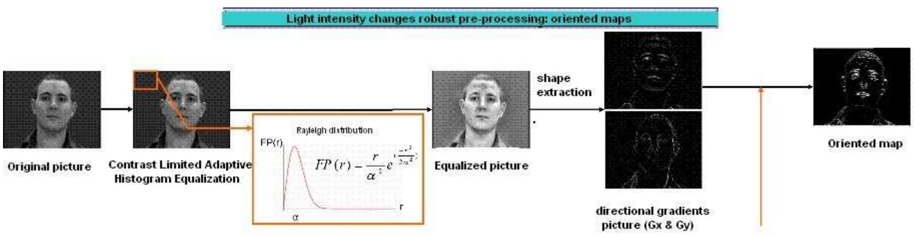
⇒ Problem resolved thanks to the use of several cameras (with a face detector incorporated)

Weak sturdiness to light changes

⇓ Pre-processing of 2D textures laid on face models

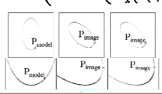


face characteristic points precise positioning: 2DAAM



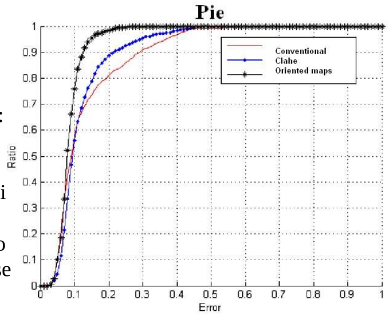
Replaces original textures,
By the shapes angle, after a
histogram equalization step

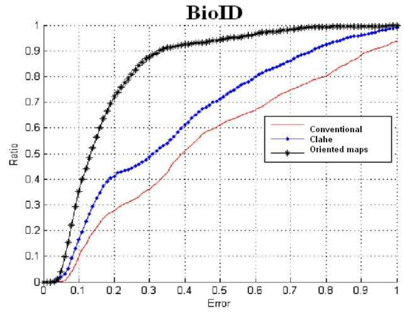
$$CO[i,j] = abs\left(\arctan 2\left(\frac{G_y(I(i,j))}{G_x(I(i,j))}\right)\right)$$



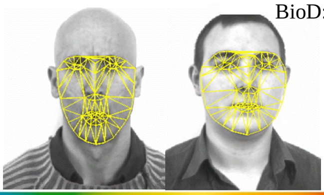
face characteristic points precise positioning: 2DAAM

Pie=PIE : CMU Pose, Illumination and Expression database





BioD:Biometric Identification Database



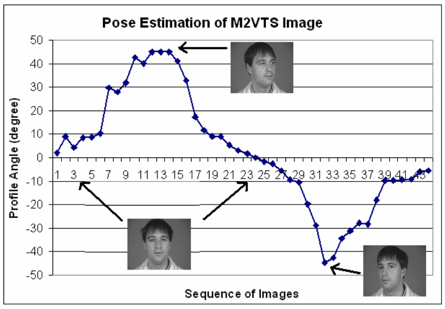
- Face Recognition, expression detection can be performed by 2D AAM but pose estimation requires 3D AAM. Moreover facial features are well localized by 3D AAM.
- 3D AAM is a little different than 2D AAM. In learning phase we need 3D shapes. Same 68 Points are marked manually on frontal and profile view of a face as shown in figure below.

3DAAM Learning

3D AAM

Sattar A, Aïdarous Y, Séguier R, *GAGM-AAM: A Genetic Optimization with Gaussian Mixtures for Active Appearance Models*, 15th International Conference on Image Processing (ICIP 2008), San Diego, California, USA, 12-15 October 2008.

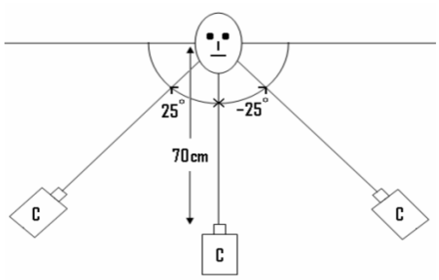
Application layer sensors



Results of Pose estimation of M2VTS Images by 3DAAM

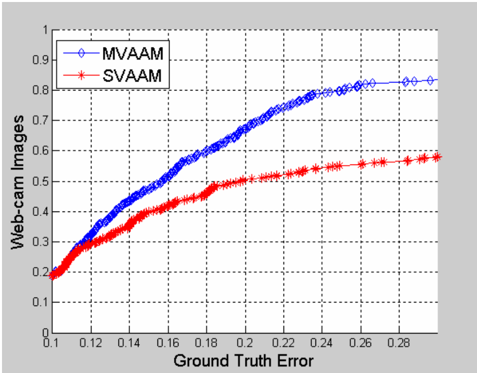
Application layer sensors

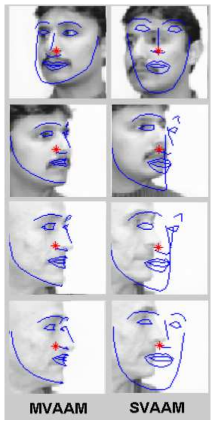
- 3D AAM can be rendered on images obtained from multiple cameras. (MVAAM)
- It needs MultiObjective optimization: NSGA-II (Non-Dominating Sort Genetic Algorithm)
- Better pose estimation compared to Single-View AAM (SVAAM).



MultiView images acquisition system

Application layer sensors





Comparison of MVAAM with SVAAM

Cognitive Cycle Challenges

Intermediary layer sensors

- Dedicated pilot channel spectrum recognition
- Geo localization spectrum recognition
- Standards blind recognition

Intermediary layer sensors

Standards

Standard	Channel bandwidth	Channel Filter	Identification
DCS 1800/DCS 1900	200 kHz	Gaussien 0.3	Yes
PDC	25 kHz	REC (Nyquist) 0,5	Yes
CT2	100 kHz	Gaussien 0.5	Yes
GSM	200 kHz	Gaussien 0.3	Yes
EDGE	200 kHz	Linearized Gauss	Yes
GPRS	200 kHz	Gaussien 0.3	Yes
PHS	300 kHz	Nyquist 0.5	Yes
RLAN Bluetooth	1 MHz	Gaussien 0.5	Yes
IS95	1.25 MHz	FIR	Yes
Globalstar	1.25 MHz	RIF 48 coeff	Yes
DAB	1.712 MHz	Gat (Window)	Yes
DECT	1.728 MHz	Gaussien 0.5	Yes
UMTS	5 MHz	Nyquist 0.2	Yes
DVB-T	7–8 MHz	Gat (Window)	Yes
DVB-S		REC (Nyquist) 0,3	Yes
RLAN	10 MHz	Nyquist	Yes
Hiperlan I	20 MHz	Gaussien 0,5	Yes
LMDS	36 MHz	Nyquist 0.2	Yes
Hiperlan II	50 MHz	Gat (Window)	Yes

Standard	Channel bandwidth	Filter	Identification
W-CDMA	5 MHz	Root raised cosine α = 0.22	-
TD-SCDMA	1.6 MHz	Root raised cosine α = 0.22	-
TIA/EIA-95A/B	1.23 MHz (US and Korea) 1.25 MHz (other countries)	Chebychev low pass (FIR)	-
cdma2000 (1xRTT)	1.23 MHz (US and Korea) 1.25 MHz (other countries)	Chebychev low pass (FIR)	-
1xEV-DO	1.23 MHz (US and Korea) 1.25 MHz (other countries)	Chebychev low pass (FIR)	-
1xEV-DV	1.23 MHz (US and Korea) 1.25 MHz (other countries)	Chebychev low pass (FIR)	-

Standard	Channel bandwidth	Filter	Identification
HSDPA	5 MHz	**Root raised cosine** (α = 0.22)	-
TETRA	25 kHz	**Root raised cosine** (α = 0.35)	-
HSDPA/HSUPA	5 MHz	HPSK : **RRC** filter (α= 0.22) QPSK&16QAM : RRC filter (α = 0.22)	-
TD-SCDMA	1.6 MHz	**Root raised cosine** filter (α= 0.22)	-
HSDPA	1.6 MHz	RRC filtered (rolloff = 0.22), *(QPSK and 16QAM)*	-
cdmaOne (TIA/EIA-95A/B/C)	1.23 MHz (U.S. cellular band) 1.25 MHz (other bands)	Chebychev low pass (**FIR**) OQPSK, 1 bit/symbol (RL) QPSK, 1 bit/symbol (FL)	-
cdma2000® (1xRTT)	1.23 MHz (U.S. cellular band) 1.25 MHz (other bands)	Chebychev low pass (**FIR**) QPSK/HPSK, 2 bits/symbol (RL) QPSK, 2 bits/symbol (FL)	-
1xEV-DO	1.23 MHz (U.S. cellular band) 1.25 MHz (other bands)	Chebychev low pass (**FIR**) QPSK/HPSK, 8PSK, 3 bits/symbol (RL) QPSK, 8PSK,16QAM (FL)	-
TETRA/TEDS (TETRA release 2)	25 kHz	RRC **filter (α= 0.35)** TETRA: π/4 DQPSK (differential QPSK) TEDS: 8DQPSK, 16QAM, 64QAM, DPSK	-
APCO 25	12.5 kHz and 6.25 kHz	CQPSK, C4FM with **RRC** filter	-

IEEE 802.15.1 Bluetooth	**1 MHz**	Gaussien 0.5	**confusion**
IEEE 802.15.3a (UWB, 3.1-10.6 GHz)	WiMedia: 528 MHz (528 MHz or greater)	Filter depends on format: Shaped pulse or frequency switched OFDM	-
IEEE 802.15.4 (Zigbee)	915 MHz: 2 MHz 2.4 GHz: 5 MHz	900 MHz: BPSK with RRC filter 2.4 GHz: OQPSK with half sine wave impulse response	-
IEEE802.16a	1.25 - 20 MHz	-	-
IEEE802.16d (WiMax, fixe)	20 MHz	square-root raised cosine (α=0.25)	-
IEEE802.16e (WiMax_Mobile, IEEE 802.16-2004)	20 MHz *(up to 10 MHz)*	*square-root raised cosine (α=0.25)*	-
HomeRF	1 MHz, 3.5 MHz	Gaussien 0.5	-

Intermediary layer sensors

spectrum ETIQUETTE 1/3

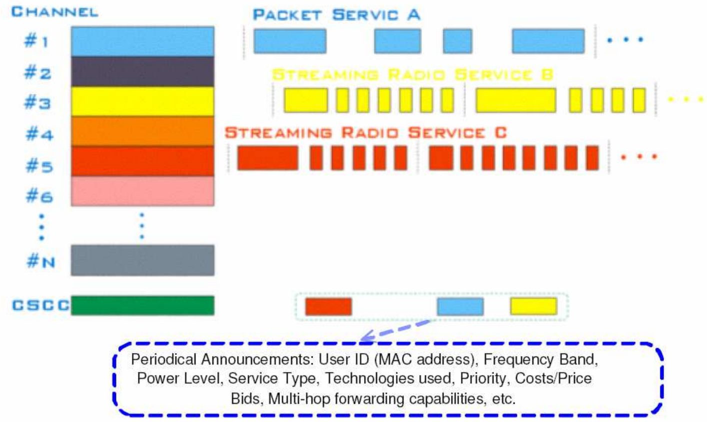
Common Spectrum Coordination Channel (CSCC) [1]

- CSCC is a narrow band channel shared by all users
- Exchange of control information
- Each user periodically broadcast its spectrum usage information over the control channel
  - » Frequency band
  - » Transmit power
  - » ID
  - » ...
- Observation gives a map of spectrum activity
- When a new user will use, it transmits a contention message, etiquette procedure to share the resource

[1] D. Raychaudhuri, X. Jing, "A Spectrum Etiquette Protocol for Efficient Coordination of RadioDevices in Unlicensed Bands", 14th IEEE 2003 International Symposium on Persona1, Indoor and Mobile Radio Communication Proceedings (PIMRC), Beijing, September, 2003.

spectrum ETIQUETTE 2/3

Common Spectrum Coordination Channel (CSCC) [1]

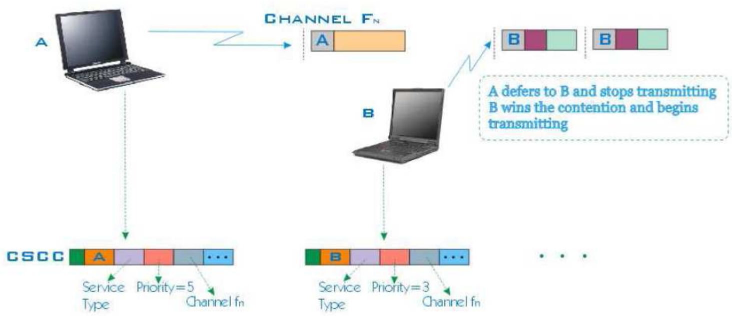


[1] D. Raychaudhuri, X. Jing, "A Spectrum Etiquette Protocol for Efficient Coordination of RadioDevices in Unlicensed Bands", 14th IEEE 2003 International Symposium on Persona1, Indoor and Mobile Radio Communication Proceedings (PIMRC), Beijing, September, 2003.

spectrum ETIQUETTE 3/3

Common Spectrum Coordination Channel (CSCC) [1]

- A uses Fn
- B listens CSCC
- No channel free
- Compete for usage with A
- Higher Priority then A stops



[1] D. Raychaudhuri, X. Jing, "A Spectrum Etiquette Protocol for Efficient Coordination of RadioDevices in Unlicensed Bands", 14th IEEE 2003 International Symposium on Persona1, Indoor and Mobile Radio Communication Proceedings (PIMRC), Beijing, September, 2003.

- Dedicated pilot channel spectrum recognition
  - CPC = Cognitive Pilot Channel
  - Downward radio link
  - Informations
    - » Frequency bands
    - » Radio access technologies (RAT)
    - » Services
    - » ...

P.Houzé, S. Ben Jemaa, P. Cordier, "Common Pilot Channel for network selection," IEEE VTC in spring conf., Melbourne, May 2006.

- Dedicated pilot channel spectrum recognition
  - Advantages
    - » Reduced coupling time
    - » Eases spectrum management and unfolding
  - Disadvantages
    - » Dedicated band, known in each region
    - » Unique frequency (agreement between operators)
    - » Uses spectrum
  - Solution studied in E^2R and proposed to several different standardization bodies

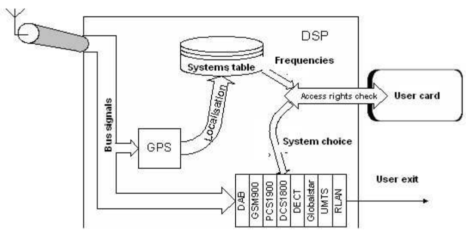
Intermediary layer sensors

- Geo localization spectrum recognition
- Hypothesis: in each geographic location and at each time, a known predefined set of accessible standards exits
  - ➢ Geo localization + Systems table = available standards

C. Roland, J. Palicot, « Un Terminal Multistandard Utilisant le GPS pour se Configurer », ISVIC 2000,Rabat(Maroc),17-20 Avril 2000

Intermediary layer sensors

- Geo localization spectrum recognition



System structure

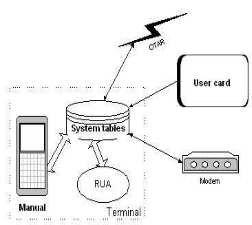
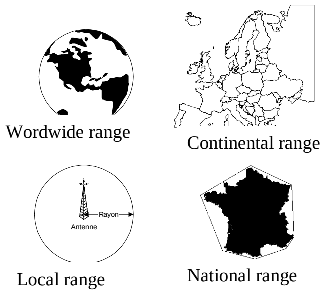
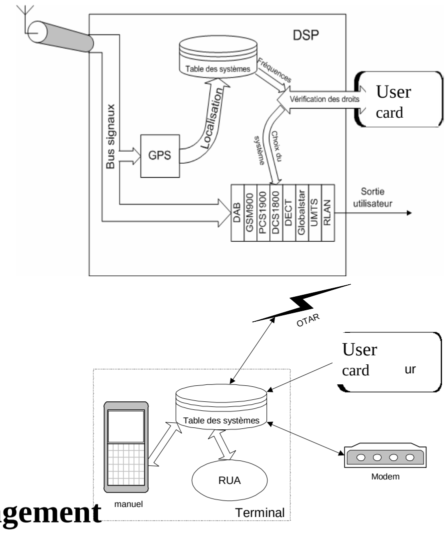


Table management

Intermediary layer sensors

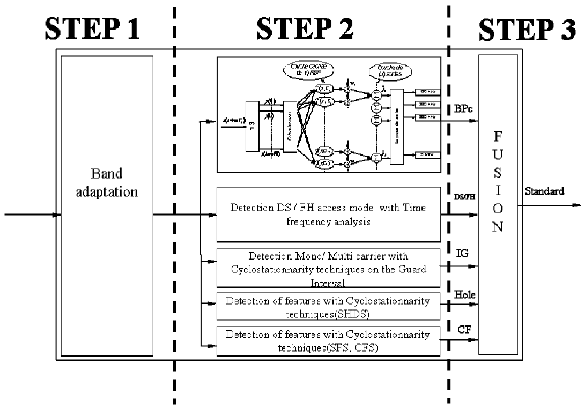




Main drawback: the table management

Intermediary layer sensors

Standards blind recognition



R. Hachemani, J. Palicot, C Moy , *A new standard recognition sensor for cognitive radio terminal*, EUSIPCO 2007, 3-7 september 2007, Poznan, Poland

Intermediary layer sensors

When reaching the receiver, the signal is an addition of standards: $x(t)=\sum_{s=1}^{S} S_s(t)$

$$x(t)=\sum_{s=1}^{S}\sum_{p=1}^{P_s}\left(fem_s(t)*m_{s,p}(c(t))\right)\exp(2\pi j f_{s,p}t)$$

With $f_{ems}(t)$ the shape filter and $m_{s,p}(c(t))$ the carrier p modulation for standard s

After sampling at f_e we obtain the following equation where $h_p(t)$ is the channel impulse response for f_p, and b(t), the noise. This signal is processed at the sensor input.

$$x(kT_e)=\sum_{s=1}^{S}\sum_{p=1}^{P} h_{s,p}(kT_e)*\left(fem_s(kT_e)*m_{s,p}(kT_e)\exp(2\pi jk\, {}^{f_p}/_{f_e})\right)+b(kT_e)$$

Intermediary layer sensors

1^{st} STEP: Analysed band adaptation

- Ratio between the smallest band needed to be detected and the analysis band is too big 10^4
- Periodogram conventional energy detection
- Filtering and decimation on each side of these energy peaks
- Disadvantage when detecting too weak signals

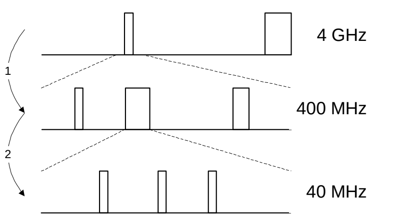


Figure : Iterative process for the Wide-Band Reduction

2^{nd} STEP: Analysis with several sensors

Example of physical layer sensors:

- Channel bandwidth (Neuronal networks RBF)
- DS / FH Access type distinction (time/frequency analysis)
- Mono/multi carriers detection (cyclostationary on GI)

3^{rd} STEP: Fusion

- **In order to increase the good recognition rate by means of:**
  - Use of simple logical rules
  - Use of Neuronal Networks
- **An example:** A simple logical rule applied to both following sensors
  - Guard interval
  - Channel bandwidth

⇨ Increases DAB / DECT distinction

Standard	Without GI	With GI
DECT	47 %	96 %
DAB	50 %	89 %

Intermediary layer sensors

COMPARAISON								
Methods	Need of an External service Provider	Content level (1)	Coverage dependant(2)	Computational complexity	Standardization process	Spectrum consuming	Operator dependent	Need of an additional link
CPC	Yes	High	yes	low	Yes	yes	Yes	Yes (CPC itself)
LBI	Yes	Medium	no	medium	No	yes	Yes	Yes (GPS)
BSRS	No	low	no	high	No	No	No	No

(1):this metric means that the information given by the method is higher with CPC than With BSRS; In fact CPC will give in addition information about the standard, the operators, the services,…Whereas BSRS will only give an information of existence of Standards (to reach more information imply to demodulate the standard)
(2):this metric means that the information given by the method is dependant of the coverage. In fact it is difficult to imagine that CPC gives precise information on Wifi standards in a small specific area whereas BSRS could detect these standards as well as LB under the assumption the data base is correctly filled.

Reading this table, it is very clear, in our point of view, that BSRS outperforms for 7 of the 8 criteria.

Cognitive Cycle Challenges

Physical layer sensors

- Bandwidth blind recognition
- Mono/Multi carriers detection
- FH/DS-SS Detection
- Available bands detection (Hole detection)

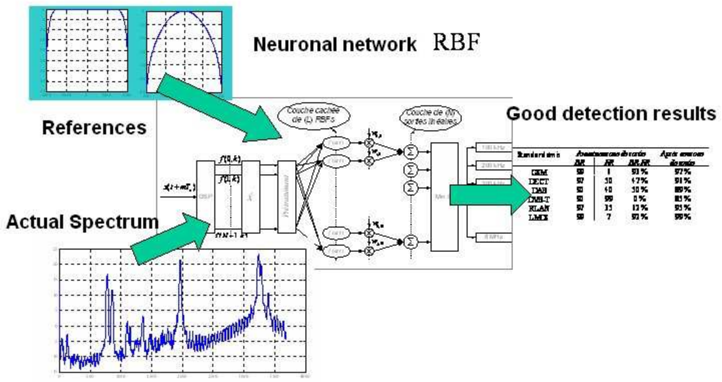
Bandwidth blind recognition

- (Power spectral densities +shaping filter)comparison

$$C_i(l) = \gamma_{\text{mod},\ i}\left(l\frac{L_{FFT}}{f_e} - L_i\right) \times \left|Fem_i\left(l\frac{L_{FFT}}{f_e} - L_i\right)\right|^2$$

- Thanks to RBF Neuronal Networks

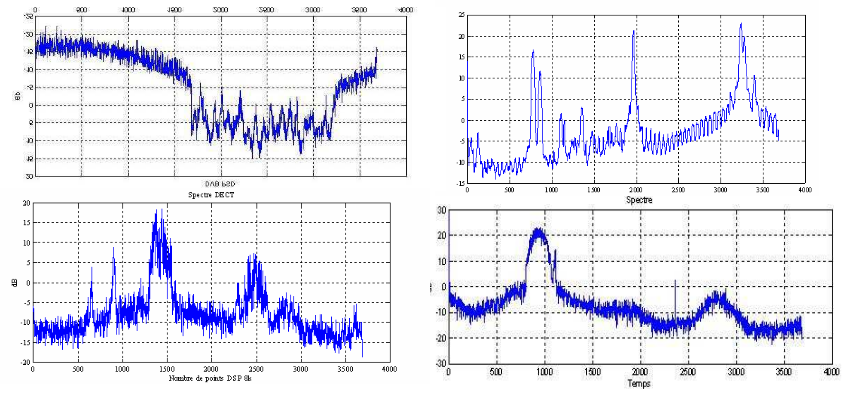
Bandwidth blind recognition



Bandwidth blind recognition

Example of sampled signals:

DVB GSM

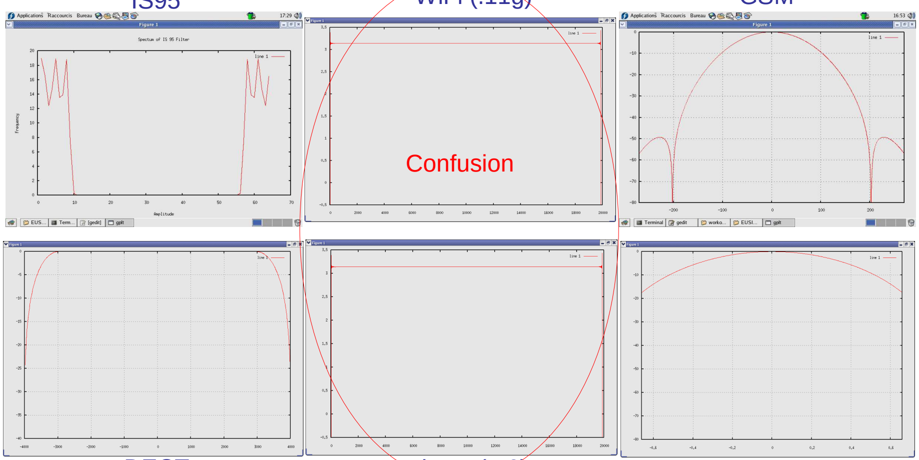


DECT DAB

Bandwidth blind recognition

Reference DSP examples:

IS95 WiFi (.11g) GSM



DECT WiMax (.16) LMDS

Bandwidth blind recognition

This lowest value will be the maximum value of the RBF threshold

Results obtained for the channel bandwidth sensor

References

Stimulus

	CT2	GSM	PHS	DECT	IS95	DAB	UMTS	DVB	LMDS	.11.g	.15.4	.11b	.15.1
CT2	0.000	0.021	0.533	2.001	12.698	18.159	47.85	138.01	93.467	440.131	60.22	2.311	2.311
GSM	0.013	0.000	0.126	0.902	6.869	9.853	25.154	73.011	49.264	232.094	31.53	2.311	2.311
PHS	0.084	0.039	0.000	0.086	1.768	3.121	8.68	25.168	16.880	77.786	10.44	0.134	0.134
DECT	0.109	0.099	0.033	0.000	0.136	0.497	3.224	10.110	6.680	28.874	3.821	0.0003	0.0003
IS95	0.117	0.127	0.115	0.030	0.000	0.398	2.934	7.092	4.864	17.862	2.505	0.016	0.016
DAB	0.117	0.127	0.115	0.082	0.185	0.000	1.352	3.800	2.502	10.126	1.346	0.052	0.052
UMTS	0.117	0.127	0.115	0.115	0.185	0.249	0.000	2.334	1.161	4.238	0.519	0.121	0.121
DVB	0.117	0.127	0.115	0.115	0.185	0.249	0.352	0.000	0.078	0.642	0.051	0.121	0.121
LMDS	0.117	0.127	0.115	0.115	0.185	0.249	0.352	0.111	0.000	1.408	0.106	0.121	0.121
.11g	0.117	0.127	0.115	0.112	0.181	0.242	0.272	0.060	0.112	0.000	0.002	0.117	0.117
.15.4	0.117	0.114	0.114	0.110	0.177	0.236	0.218	0.039	0.060	0.027	0.000	0.114	0.114
.11b	0.111	0.105	0.045	0.0002	0.068	0.288	2.526	8.631	5.641	24.221	3.177	0.000	0.000
.15.1	0.111	0.105	0.045	0.0002	0.068	0.288	2.526	8.631	5.641	24.221	3.177	0.000	0.000

Confusion

Confusion Matrix calculated with MSE error $_{comb}$

$$MSE_{Comb} = \frac{1}{L_i} \sum_{l=1}^{L_i} ((\gamma_l - C_{i,l})^2 \times |\log(\frac{\gamma_l}{C_{i,l}})|)$$

FH/DS-SS Detection

- Approach inspired by M.Gandetto works[1]
- Time frequency analysis with Wigner-Ville transform
- Two parameters:
  - Tmax : Signal maximum period
  - Std : Instantaneous frequency deviation

$x(t)$ → W-V T → T_M, $std(\omega)$

$$W(t,\omega) = \frac{1}{2\pi} \int x(t+\frac{\tau}{2}) x^*(t-\frac{\tau}{2}) e^{-j\omega\tau} d\tau$$

$$T_M = \max(T(\omega))$$

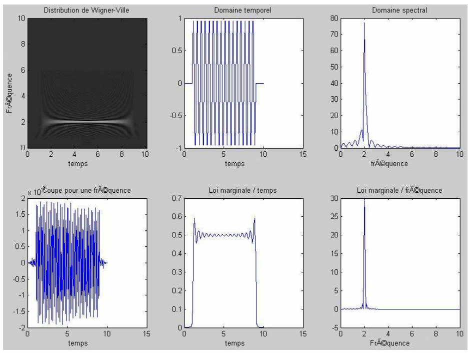
$$std(\omega) = \frac{1}{T} \sum (\omega_i - \overline{\omega}_i)^2$$

[1] M. Gandetto, M. Guainazzo and C. S. Regazzoni. "Use of time-frequency analysis and neural networks for mode identification in a wireless software-defend radio approach". Eurasip Journal of Applied Signal Processing, Special Issue on Non Linear Signal Processing and Image Processing, 13:1778-1790, October 2004.

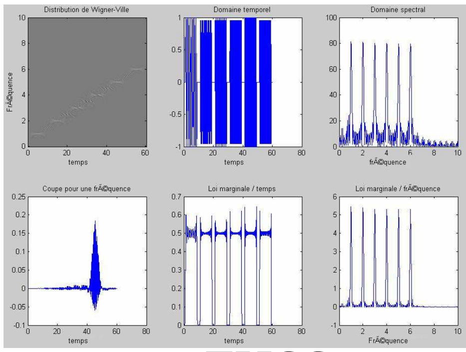
FH/DS-SS Detection

Time Frequency Analysis:
Wigner-Ville Distribution

	Bluetooth IEEE 802.15.1	WiFi IEEE 802.11b
Bandwidth	1MHz	1MHz
Shape filter	Gauss 0.5	Gauss 0.5
Spreading	FH	DS



DSSS



FHSS

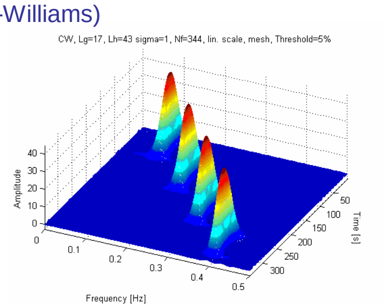
Cross terms : Interferences

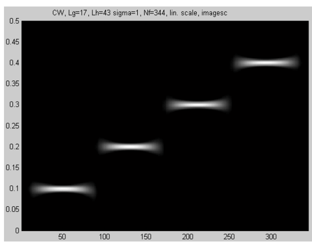
FH/DS-SS Detection

Time Frequency Analysis:
(Choi-Williams)

Preliminary results

Results for threshold of the distribution of energy.



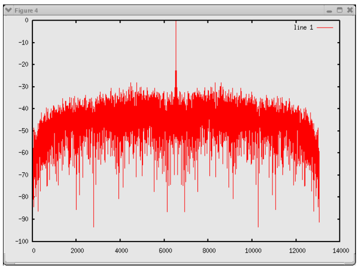


Performance results for detection versus SNR

FH/DS-SS Detection

• Usually, multicarrier systems use a Guard Interval (GI)
• This GI generates a cyclic frequency
• This frequency detection provides mono/multi information

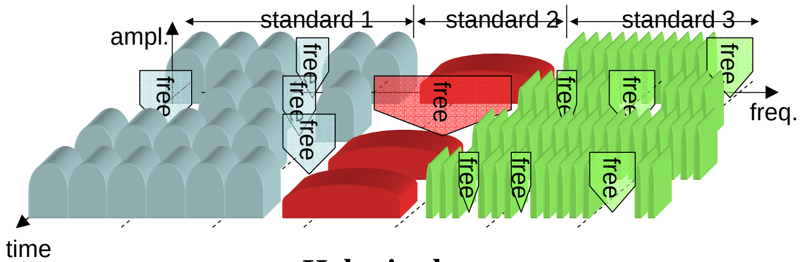
$$\varphi_x(k) = E\{x(l)x(l-k)\}$$



OFDM signal RI detection

(Symbol OFDM 2K, obs=16K, IG/Tu=1/16)

Spectrum Hole detection



Holes in the spectrum

- **Need to detect them (Filtering and detection)**
- **Agreement between TX and Rx**
- **Then need**
  - **to characterize the hole (the noise level, the interference level...)**
  - **To identify the impulse response between the Rx and the Tx in this hole**

Filtering problem (1/6)

Technically unfeasible to check all the band

→ **Scan**

Or Specific filtering

Filtering problem (2/6)

- **In one predefine band**
  - Ex: Check if one GSM channel is free in the GSM band
- **Whatever the band is**
  - Ex: Check if a desired Bandwidth(ex 1MhZ) is free in the band [1MhZ; 3 GhZ]

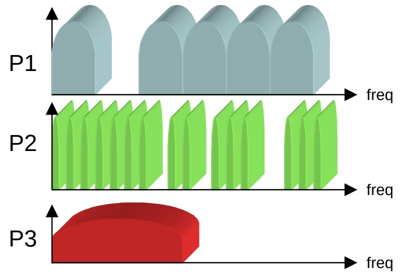
→

- **The solution will be different**

Supélec

Filtering problem (3/6)

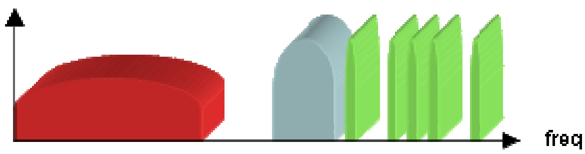
- FB should be able to extract channels spaced with different values. We only consider here a sequential extraction.



Supélec

Filtering problem (4/6)

- FB should be able to extract channels with different bandwidths simultaneously.

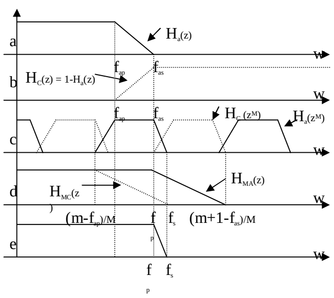


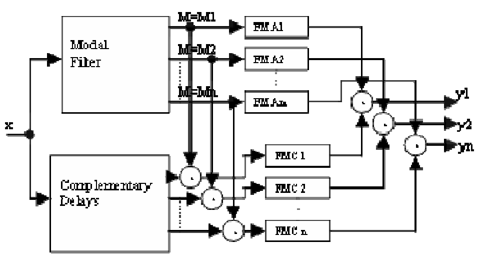
Filtering problem (5/6)

- **FB must be able to be selective enough with a reasonable complexity as very sharp filtering expectations may be demanded, especially if the bandwidth of channels is small compared to the wideband acquired signal.**

Filtering problem (6/6)

- **Classical FB filters does not meet these requirements. A new scheme has been recently proposed based on FRM technique [1]**





T. Hentschel, "Channelization for software defined base-stations," Annales des Telecommunications, ISSN 0003-4347, vol. 57, pp. 386-420, no. 5-6, May-June 2002.

[1]R. Mahesh,A. P. Vinod, C Moy, J Palicot, "A Low Complexity Reconfigurable Filter Bank Architecture for Spectrum Sensing in Cognitive Radios", CROWNCOM 2008, Singapour

Spectrum Hole detection

In each band the algorithm detection should be applied

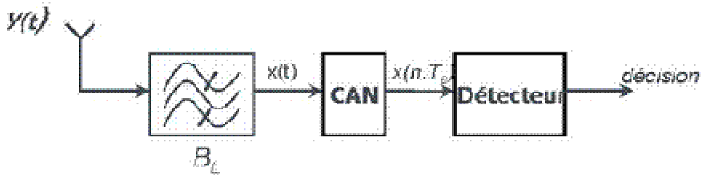
Whatever the method is

- **Energy detector**
- **Cyclostationnarity detector**
- **Covariance matrix eigenvalues detector**
- **Other….**

$H_0 : x(t) = b(t)$
$H_1 : x(t) = \sum s_i(t) + b(t),$

Spectrum Hole detection

Problem positioning



- Available band or engaged band
- Hypothesis test:

$$H_0 : x(t) = b(t)$$
$$H_1 : x(t) = \sum_i s_i(t) + b(t),$$

$H_0 : x(t) = b(t)$

$H_1 : x(t) = \sum s_i(t) + b(t),$

Problem positioning

- Radiometer:

  (+) simple efficient

  (--) requires a relevant noise level estimation

- Cyclostationary:

  (+) far less responsive to noise level variation

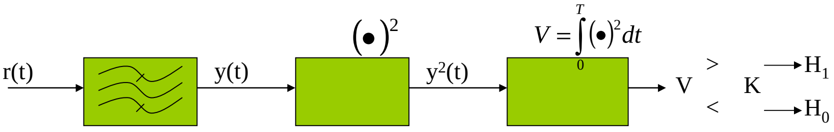
  (--) requires a prior knowledge of the cyclic frequencies that need testing

  (--) responsive to Nyquist emission filtering

➢Multi-cycle sensor

➢Blind sensor

Energy detector



- Calculates the signal energy V over a period of time T
- Calculates a detection threshold K, with $K=G.N_0$
- If V>K, decides that a signal exists
- Noise level threshold

* N_0 is the noise spectral density

Cyclostationnarity detector

$$c_{xx}(t,\tau) = E\big(x(t)x(t+\tau)\big) = c_{xx}(t+T,\tau)$$ T=cyclic period

The time varying function $c_{xx}(t,\tau)$ Can be developped according to the variable t into the following Fourier series:

$$c_{xx}(t,\tau) = c_{xx}(\tau) + \sum_{\alpha \in \psi} C_{xx}(\alpha,\tau) e^{i2\pi\alpha t}$$

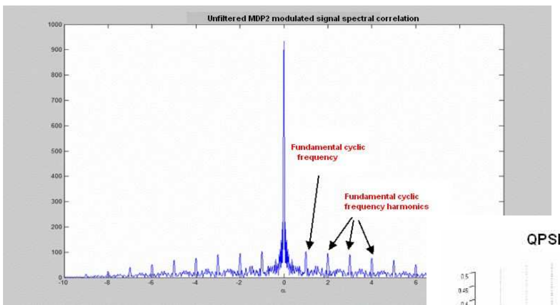
$$C_{xx}(\alpha,\tau) = \lim_{Z\to\infty} \frac{1}{Z} \int_{-Z/2}^{Z/2} c_{xx}(t,\tau) e^{-i2\pi\alpha t} dt$$

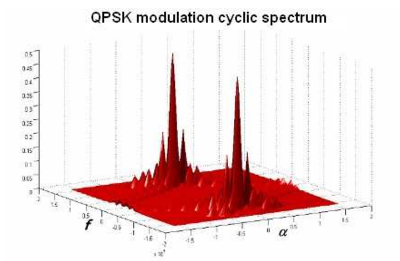
C_{xx}=cyclic covariance function
α= cyclic frequency

- Test on a cyclic frequency (Giannakis)
- Multi-cycle test[1]
- Blind test

[1] **Ghozzi M , Dohler M , Marx F , Palicot J**, *Cognitive radio: methods for the detection of free bands*, Comptes Rendus Physique, Elsevier, pp, volume 7 September 2006

Cyclostationnarity detector

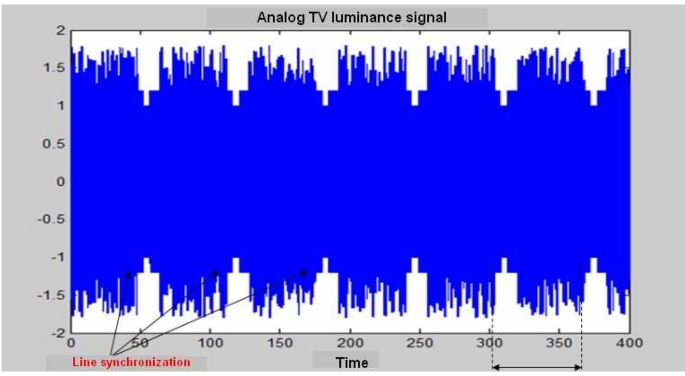




Harmonics may be filtered by Nyquist filtrer

Cyclostationnarity detector

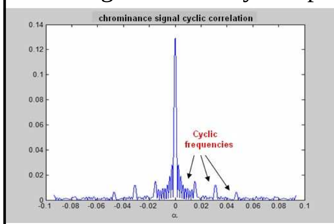
Analog television test



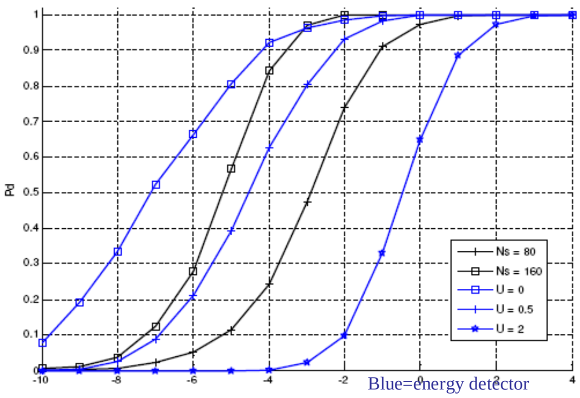
line length: 64 µs

Cyclostationnarity detector

Analog television cyclo-spectrum



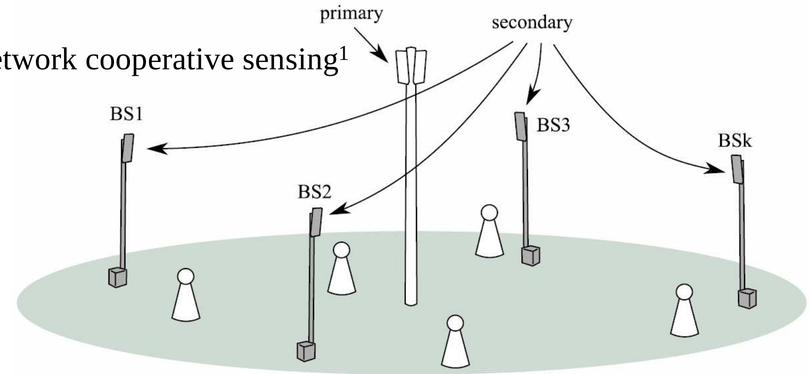
Digital television detection
With the Multi-cycle sensor



Blue=energy detector
Black=Multi-cycle detector

Covariance matrix eigenvalues detector

Network cooperative sensing[1]



Secondary base stations $\{BS_1, BS_2, BS_3, \ldots, BS_K\}$ cooperatively sense the channel in order to identify a white space and exploit the spectrum.

[1] L Cardoso, M Debbah, P Bianchi, J Najim 'Cooperative Spectrum Sensing Using Random Matrix Theory », IEEE ISWPC 2008, May 2008, Santorini, Greece.

Covariance matrix eigenvalues detector

The value of cooperation: random matrix approach

Consider the $K \times N$ matrix consisting of the samples received by all the K secondary base stations ($y_i(k)$ is the sample received by base station i at instant k):

$$\mathbf{Y} = \begin{bmatrix} y_1(1) & y_1(2) & \cdots & y_1(N) \\ y_2(1) & y_2(2) & \cdots & y_2(N) \\ y_3(1) & y_3(2) & \cdots & y_3(N) \\ \vdots & \vdots & & \vdots \\ y_K(1) & y_K(2) & \cdots & y_K(N) \end{bmatrix}.$$

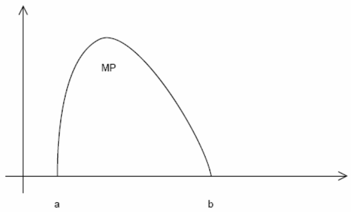
The goal of the random matrix theory approach is to predict the behavior of the $\frac{1}{N}\mathbf{Y}\mathbf{Y}^H$

If $N \to \infty$, $\frac{1}{N}\mathbf{Y}\mathbf{Y}^H \to \mathbf{I}$ (test of independence!)

Covariance matrix eigenvalues detector

Theorem. Consider an $K \times N$ matrix $\mathbf{W}$ whose entries are independent zero-mean complex (or real) random variables with variance $\frac{\sigma^2}{N}$ and fourth moments of order $O(\frac{1}{N^2})$. As $K, N \to \infty$ with $\frac{K}{N} \to \alpha$, the empirical distribution of $\mathbf{W}\mathbf{W}^H$ converges almost surely to a nonrandom limiting distribution with support

$$\begin{aligned} a &= \sigma^2(1-\sqrt{\alpha})^2 \\ b &= \sigma^2(1+\sqrt{\alpha})^2. \end{aligned}$$



and density

$$f(x) = (1-\frac{1}{\alpha})^+\delta(x) + \frac{\sqrt{(x-a)^+(b-x)^+}}{2\pi\alpha x}$$

Interestingly, when there is only noise, the support of the eigenvalues of the sample covariance matrix is finite, whatever the distribution of the noise. Moreover, the ratio does not depend on the noise variance!

Covariance matrix eigenvalues detector

Spectrum sensing algorithm: computing the ratios

The algorithm does not require the knowledge of the noise variance or the channel statistics and computes the ratio of the maximum (λ_{max}) to minimum (λ_{min})value of the sample covariance matrix of the received signal.

$$\text{decision} = \begin{cases} H_0 : & \text{, if } \frac{\lambda_{max}}{\lambda_{min}} \leq \frac{(1+\sqrt{\alpha})^2}{(1-\sqrt{\alpha})^2} \\ H_1 : & \text{otherwise} \end{cases}$$

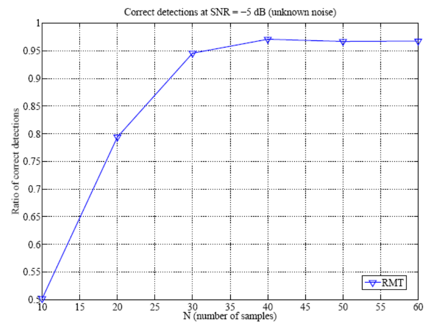
Note moreover that the test H_1 provides also a good estimator of the SNR. Indeed, the ratio of largest eigenvalue (b') and smallest (a) of $\frac{1}{N}\mathbf{Y}\mathbf{Y}^H$ is related solely to SNR and α i.e

$$\frac{b'}{a} = \frac{(\mathrm{SNR}+1)(1+\frac{\alpha}{\mathrm{SNR}})}{(1-\sqrt{\alpha})^2}$$

To our knowledge, this estimator of the SNR has never been put forward in the literature before.

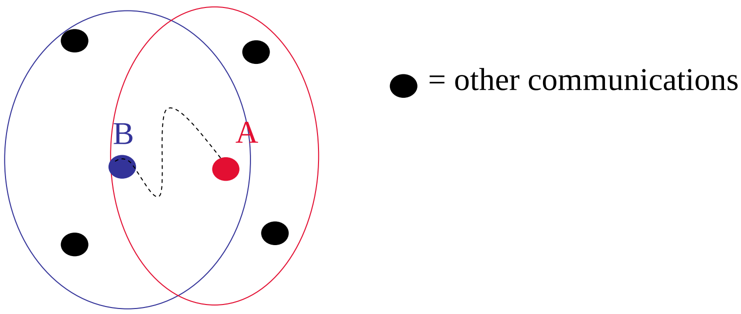
Covariance matrix eigenvalues detector

Simulations: detector performance



For $K = 10$ and $\mathrm{SNR} = -5dB$, even without the knowledge of a noise variance, one is still able to achieve a very good performance for sample sizes greater than 30.

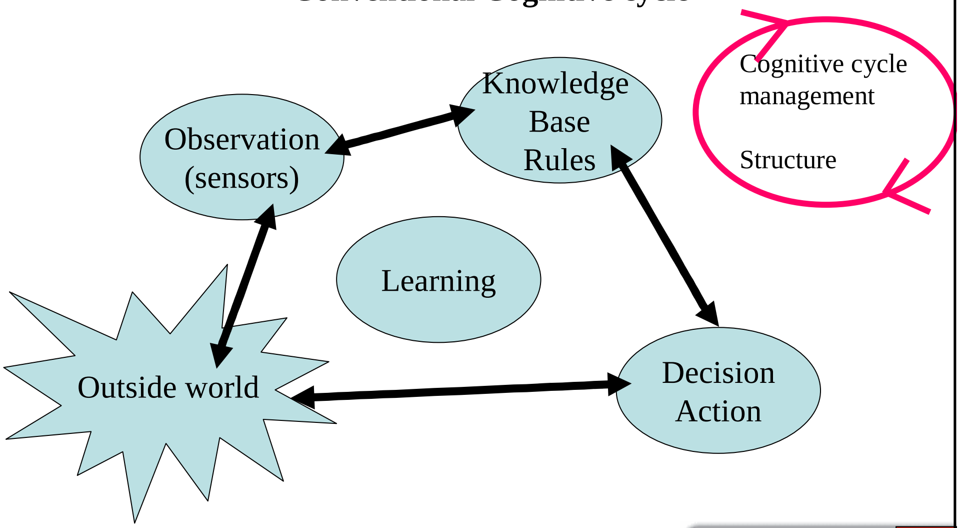
- **Agreement between TX and Rx of both A and B**
- **Then the frequency band is an opportunity**



- **To characterize this band (S/B, interference noise…)**
- **To characterize the IR between A and B (great Challenge)**

Cognitive Cycle Challenges

Conventional Cognitive cycle



Outline

- SUPELEC / SCEE presentation
- Spectrum management
  - Current situation
  - Spectrum sharing
  - Wireless capacity
- Introduction to Cognitive Radio
  - General remarks
  - A more general « View »
  - The « Sensorial Cognitive Radio Bubble »
- The Challenges
  - Cognitive Radio Challenges
    - » The sensors
    - » **The cycle management**
  - Challenges related to Software Radio technology
    - » ADC
    - » Non-linearities
    - » Execution platform
- Conclusion

The cycle management

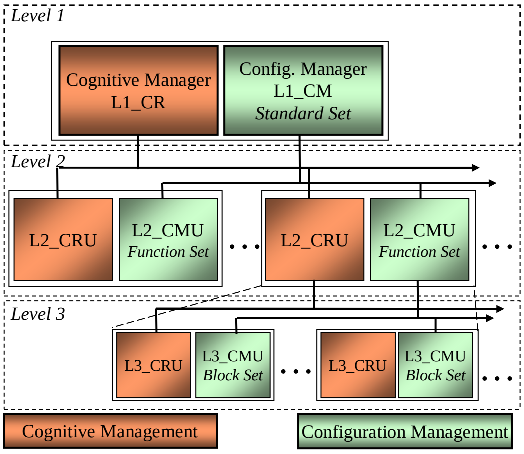
- The Hierarchical management
- A meta-model and a simulator for CR equipment management architecture
- Scenario #1: SNR adaptation

Analysis of requirements

- Reconfiguration management (discussed later; in the Challenges related to Software Radio technology)
  - different levels of granularity
  - distribution / multi-processing
  - heterogeneity of processing resources
- Cognitive management
  - collect sensing information of many kinds anywhere
  - compute metrics (local/wider impact)
  - make decisions for local impact
  - transmit information for a wider impact
  - notify the rest of the system
  - receive notification from the network

HDCRAM

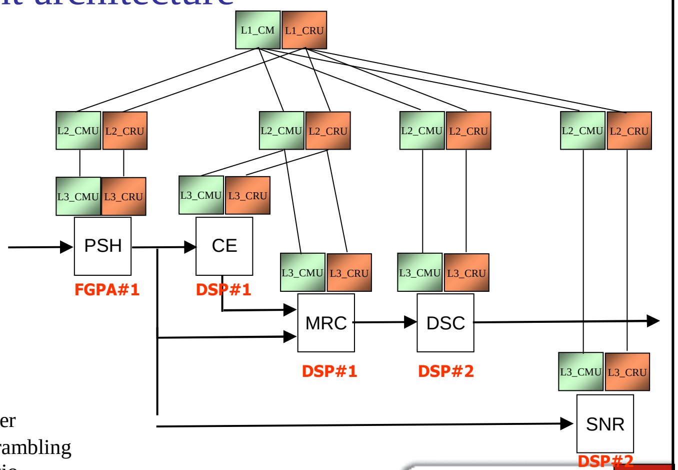
- From a configuration management
- To a CR management[1]
  - one L1_CR
  - several L2_CRUs
  - each having several L3_CRUs



[1] L. Godard, C. Moy, J. Palicot
"From a Configuration Management to a Cognitive Radio Management of SDR Systems"
CrownCom'06, 8-10 June 2006, Mykonos, Greece

UMTS FDD Rx Radio chain example

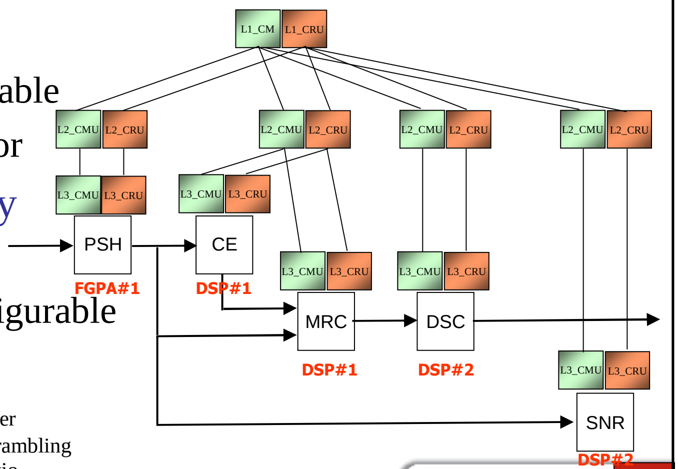
- Signal processing chain (operators/PBU)
- Management architecture
  - level 3
  - level 2
  - level 1
- Sensing operator



PBU or operators:
- PSH: pulse shaping
- CE: channel estimator
- MRC: max. ratio combiner
- DSC: despreading / descrambling
- SNR: Signal to Noise Ratio

UMTS FDD Rx Radio chain example

- Management architecture only where necessary
- If PSH is
  - neither reconfigurable
  - nor a sensor
- if CE is only a sensor
  - not reconfigurable



- PSH: pulse shaping
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The cycle management

- The Hierarchical management
- A meta-model and a simulator for CR equipment management architecture
- Scenario #1: SNR adaptation

Why a metamodel?

- Formalization of the HDCRAM
  - list all the class / metrics / concepts
  - comprehensive to everybody
    - » UML is supposed to be universal
- Re-usability
  - by anyone
    - » evaluate
    - » complete
- Simulation
  - prove the behavior
  - refine the architecture

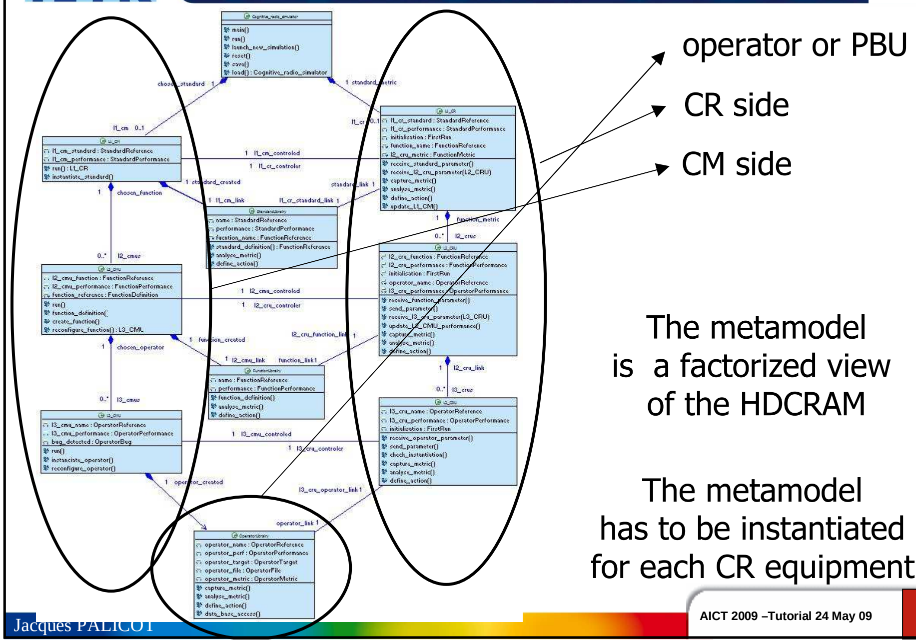
Kermeta

- UML: graphical language for object modeling
- not simulable
- *Kermeta* is an executable metalanguage from INRIA of Rennes

http://www.irisa.fr/triskell/softwares-fr/kermeta/

  - permits
    - » to describe structure and behavior of a metamodel
    - » to define new DSL (Domain Specific Language)
- Eclipse developing environment

HDCRAM metamodel

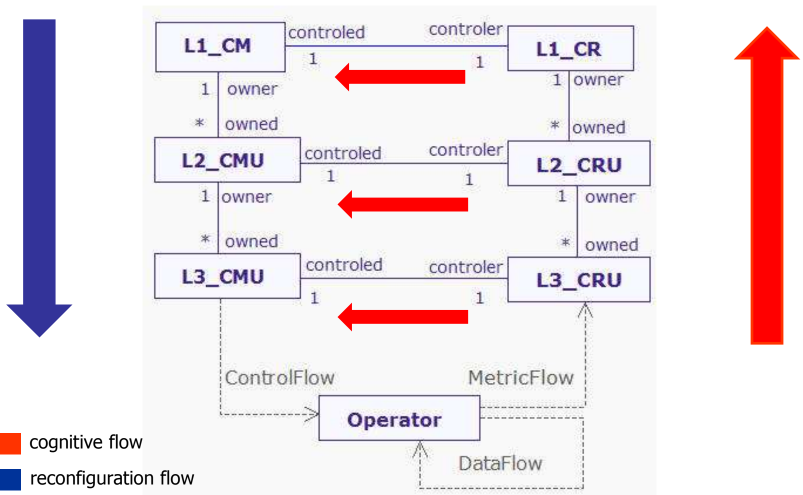


The metamodel
is a factorized view
of the HDCRAM

The metamodel
has to be instantiated
for each CR equipment

Info exchanges

- Cognitive and reconfiguration flows



cognitive flow
reconfiguration flow

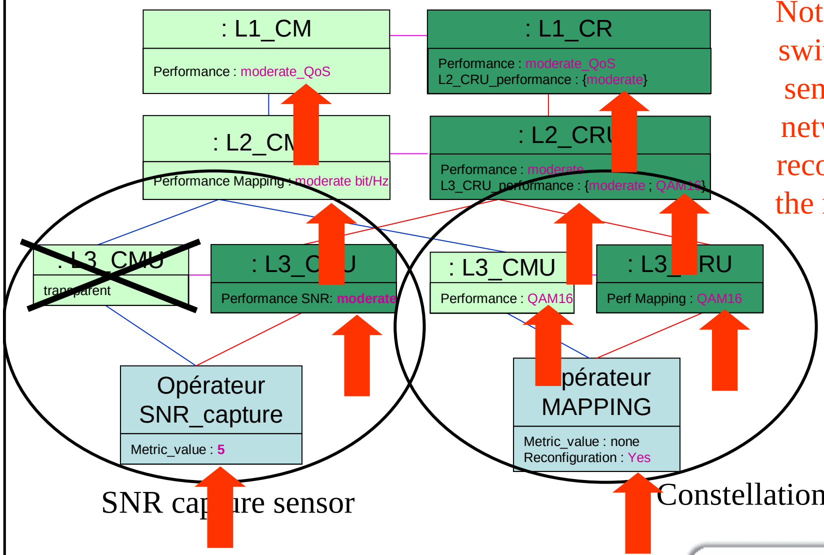
The cycle management

- A meta-model and a simulator for CR equipment management architecture
- Scenario #1: SNR adaptation

Modulation order adaptation

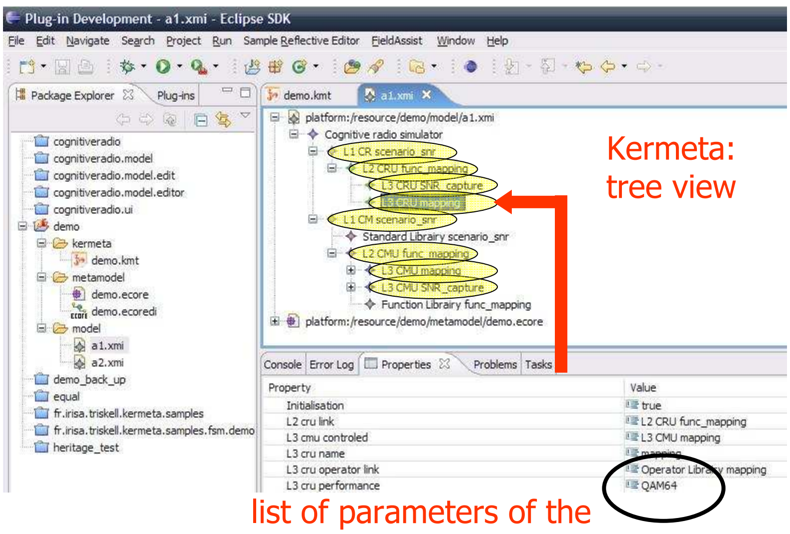
- Modulation order adaptation in function of SNR
  - High order at high SNR to increase throughput
  - Low order at low SNR to improve robustness
- 1 processing operator: mapper
  - reconfigurable operator
- 1 sensing operator: SNR capture
- Each opertor is managed by its own couple L3_CRU/L3_CMU
  - both depending on the same L2_CRU/L2_CMU

Modulation order adaptation



Not shown: switch info sent to the network to reconfigure the receiver

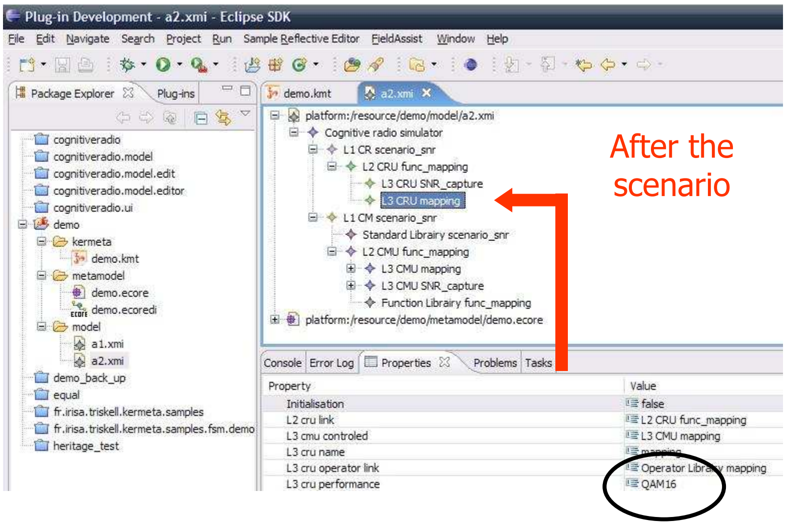
Kermeta output view



Kermeta: tree view

list of parameters of the selected operator

Kermeta output view



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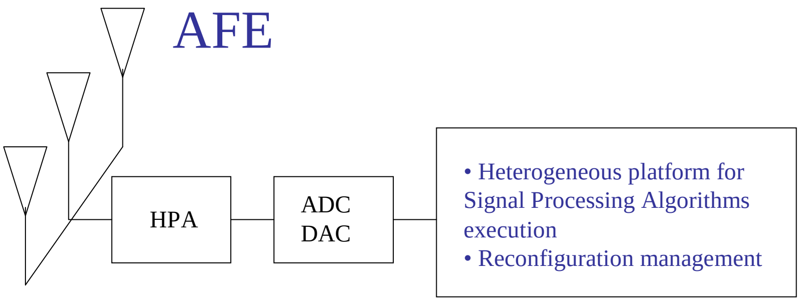
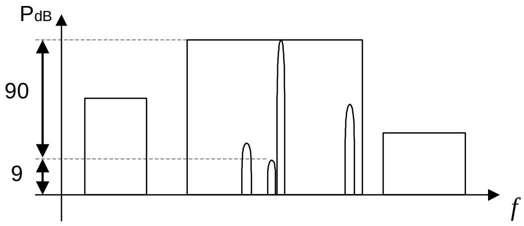
Genuine Software Radio, broad band

Broad Band Antennas



Analog to Digital Conversion



Parameters ⇨ ADC characteristics

- Bandwidth of the signal to be digitized
- min S/B to demodulate
- Others Channels power in the bandwidth
- Margin to avoid saturation

NEAR FAR EFFECT

Analog to Digital Conversion

Number of required bits as a function of the input signal

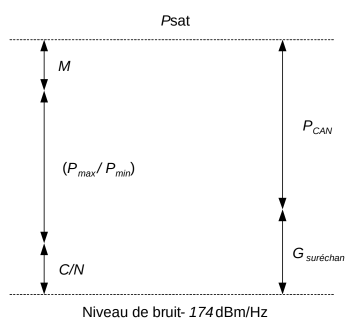
$$N = \left(10\log(S/B) - 10\log(fe/2BP)\right)/6.02 + 0.3$$

$$N \cong 1{,}661 \cdot \log(S/B) - 1{,}661 \cdot \log(fe/2BP)$$

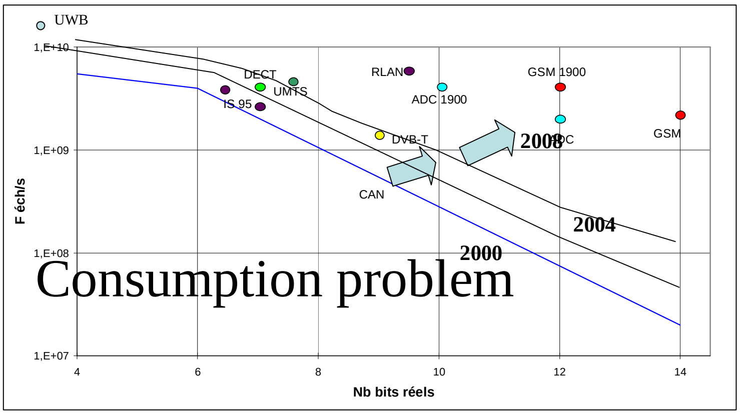
- Which corresponds to one supplementary bit per 6 dB
- Which corresponds to a decrement of about ½ bit on doubling the frequency.
- To compute the number of bits we use the previous equations.
- This bit number is equal to: $N_{réel} = N_{dyn} - N_{suréch}$
  - where N_{dyn} is the required number of bits for the considered dynamic
  - and $N_{suréch}$ is the gain due to oversampling.

Analog to Digital Conversion

This is illustrated by this scheme

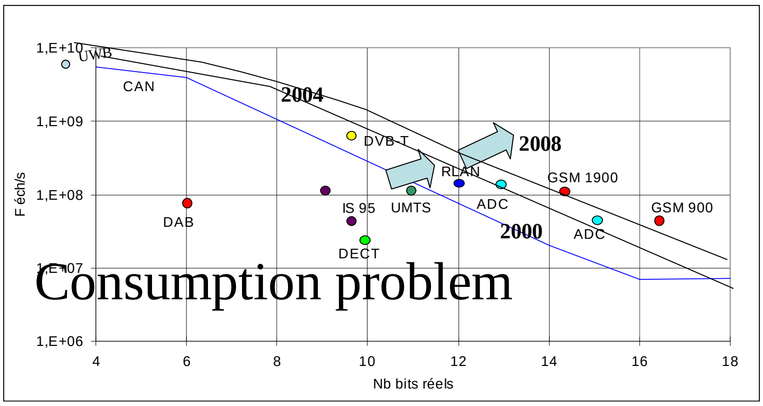


Analog to Digital Conversion



ideal SWR for the standard bandwidth

Analog to Digital Conversion

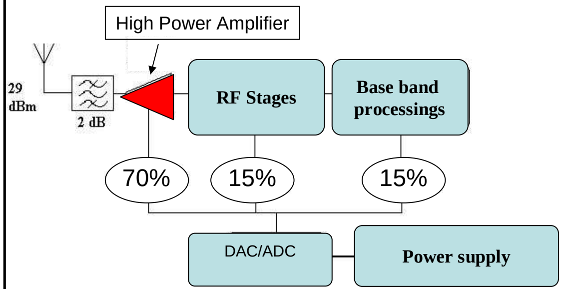


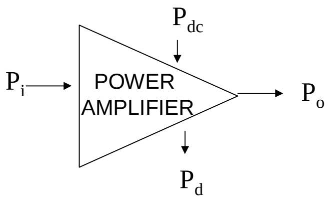
SDR with Low IF frequency architecture

Non-Linearities : Positioning of problem

A 2.5G terminal power budget:

- Power : A key factor in telecommunications
- 60-70 % of power consumption due to HPA*





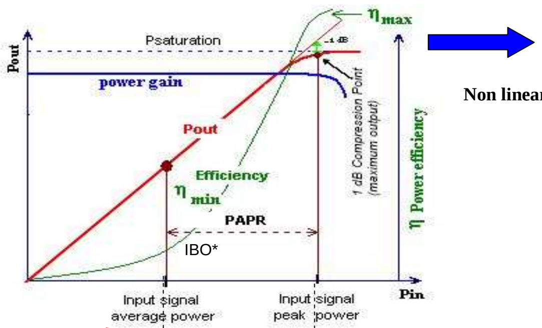
Power budget :

$$P_i + P_{dc} = P_o + P_d$$

Power efficiency : $\eta = \frac{P_o}{P_{dc}}$

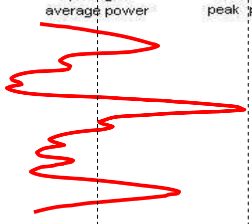
* HPA : High Power Amplifier

Non-Linearities : Positioning of problem



Non linear distortions

Signal to be amplified

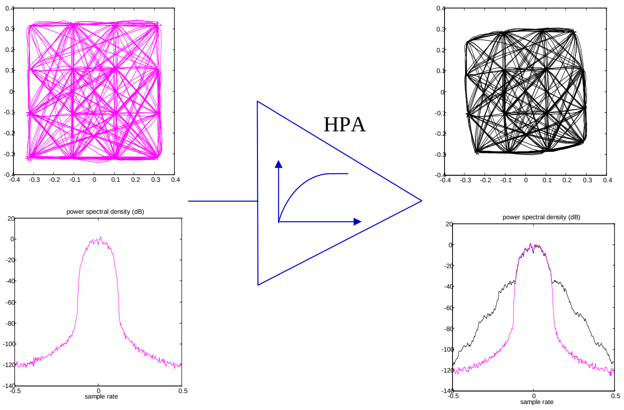


* IBO : Input Back Off

Non-Linearities : Positioning of problem

IETR | Supélec

Power Amplifier and Signal with high PAPR



1 – Mapping compression
2 –BER degradation

3 – Out of band emission
4 –Intermodulation

16-QAM Signal

PAPR Frequency View for Cognitive Radio

IETR | Supélec

- Non-linearities and PAPR Problem in Cognitive Radio
  - OFDM and Software Radio signals equivalence
  - Cognitive Radio systems : Dynamic Spectrum Access
- PAPR Frequency Domain Interpretation
  - Free spectrum access under PAPR metric constraint.

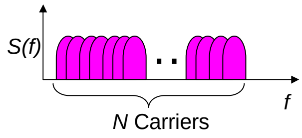
Palicot J, Louet Y, Hussain S, Zabre S, *Frequency Domain Interpretation of Power Ratio Metric for Cognitive Radio Systems*, Proceedings of IET Communications Journal, July 2008,Vol: 2, Issue:6, pp: 783-793

PAPR Frequency View for Cognitive Radio

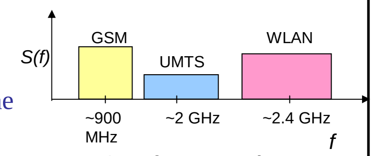
- OFDM is a multiplex of modulated carriers
  - Multicarrier nature of OFDM causes large power fluctuations.
- SWR is also a multiplex of modulated carriers
  - Case 1 : Mono Standard signals ($\Delta f = cnst$)
  - Case 2 : Multi Standard signals ($\Delta f \neq cnst$)

  => SWR signal also demonstrates large power fluctuations.
- Power fluctuations are generally described by the term PAPR (Peak to Average Power Ratio)
  - PAPR = maximum power/ average power
- As PAPR is a random variable so it is presented by its cumulative distribution function,

$$CCDF = Pr[PR > PR_0]$$



OFDM frequency view



SWR frequency view

SWR and OFDM : The Gaussian Equivalence

- For signals with large number of modulated sub-carriers N, we have shown the equivalence between OFDM and SWR PAPR distribution.

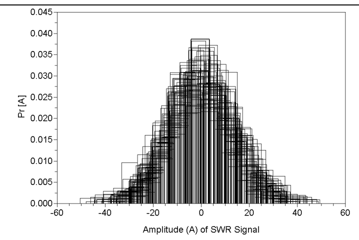
SWR=MC-GMSK+ MC-QPSK+OFDM
with N=64 L=4 for all modulations

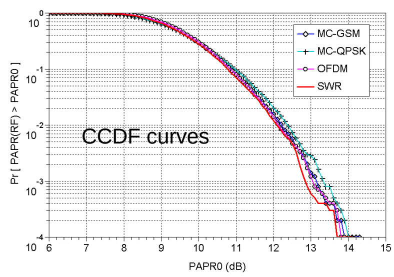
SWR signal follows classical OFDM PAPR distribution curve:

$$Pr[PR \geq PR_0] \approx 1 - e^{-\sqrt{\frac{\pi}{6}}N\sqrt{PR_0 e^{-PR_0}}}$$

Conclusions :
Equivalence between OFDM and SWR motivated to use same analysis and the same methods for PAPR mitigation as for OFDM.

Prob. Density function of real part of SWR signal

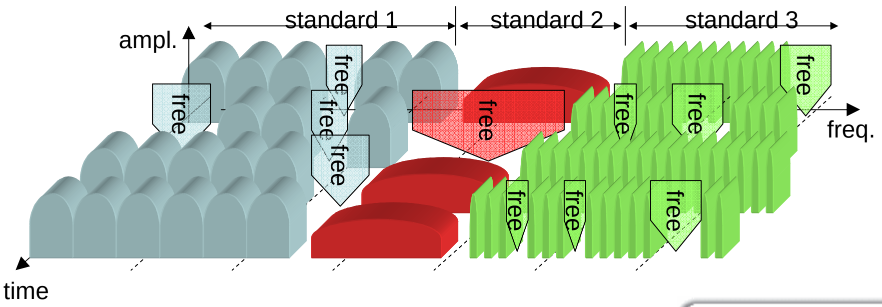




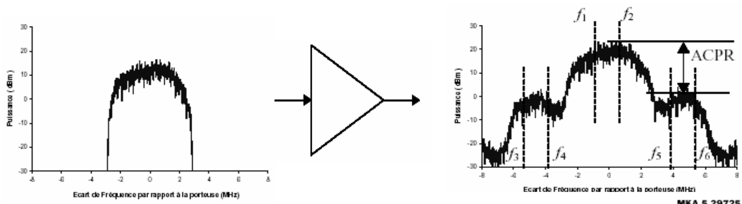
Cognitive Radio and Dynamic Spectrum Access

- Real time modification of the physical layer parameters (link adaptation).
- Insert spectrum (tones) in between standards or inside the standards (opportunistic communication).
  - Find hole, check if usable and then insert the tones

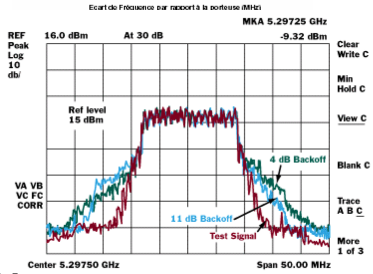
  => Global PAPR is modified



Cognitive Radio and Dynamic Spectrum Access



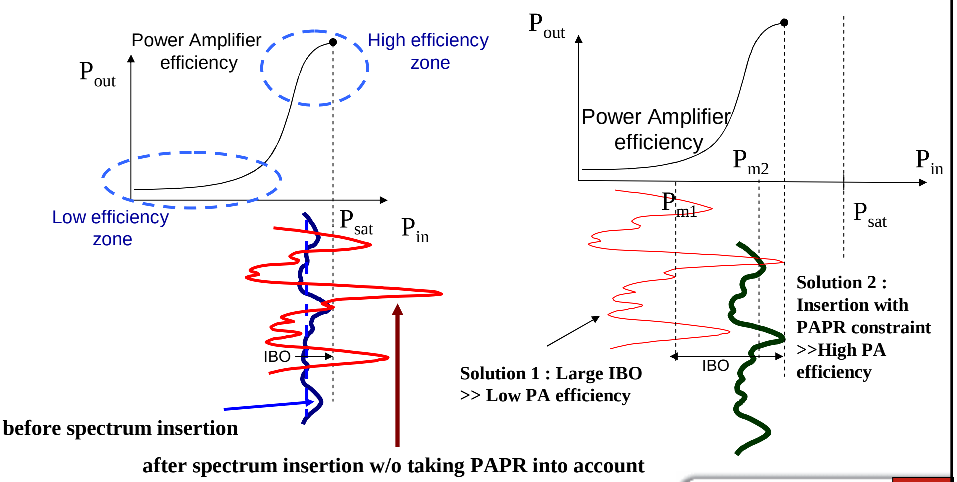
$$ACPR_{dB} = 10 \cdot \log \frac{\int_{f_1}^{f_2} P(f)df}{\int_{f_3}^{f_4} P(f)df + \int_{f_5}^{f_6} P(f)df}$$



Spectrum access should not increase the out of band power level to avoid interference with other signals

Dynamic Spectrum Access

PAPR mitigation solutions after spectrum access

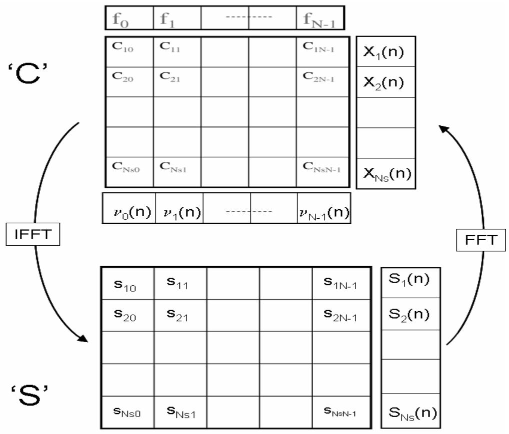


PAPR Frequency View for Cognitive Radio

- Non-linearities and PAPR problem in Cognitive Radio
  - OFDM and Software Radio signals equivalency
  - Cognitive Radio systems : dynamical Spectrum Access
- PAPR Frequency Domain Interpretation
  - Free spectrum access under PAPR metric constraint.
  - PAPR reduction methods based on adding signals in the frequency domain (tone reservation, ...).

Frequency Domain PAPR Interpretation (1/6)

- In OFDM frequency symbols 'C' are tabulated as carrier per carrier.
- If Ns (Number of OFDM symbols) increases, PAPR approches theoretical upper bound.
- Rows and columns interchangeable for PAPR calculations.



$$\sum_{r=1}^{N_s}\sum_{c=1}^{N} C_{c,r}\exp(\iota 2\pi rc/N) = \sum_{c=1}^{N}\sum_{r=1}^{N_s} C_{c,r}\exp(\iota 2\pi rc/N)$$

Goal : Express (time) PAPR vs individual carrier PAPR
Each carrier PAPR being very easy to compute

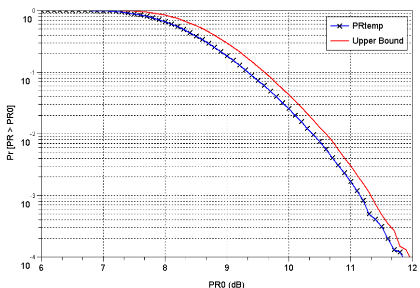
Frequency Domain PAPR Interpretation (2/6)

$$PR_{N_s}(S(n)) \leq \frac{(\sum_{k=1}^{N} P_m(k)\times PR_{f_k}) + \max_{k\in K}(\max_{j\in J}(\lambda(j,k)))}{\sum_{k=1}^{N} P_m(k)} \quad (1)$$

where

$$\lambda(j,k) = \sum_{p=1}^{N} C_{j,p}\sum_{p'\neq p}\overline{C_{j,p'}}e^{2i\pi\frac{k(p-p')}{N}}, j\in J, k\in K.$$

- It demonstrates that PR_{temp} is upperbounded by relation (1) which depends only on frequency components.



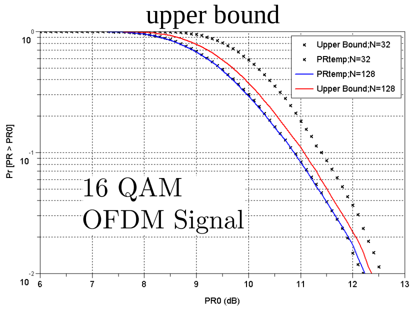
16 QAM
64 Carrier
OFDM Signal

Upperbound and PR_temp distribution for OFDM

Frequency Domain PAPR Interpretation (3/6)

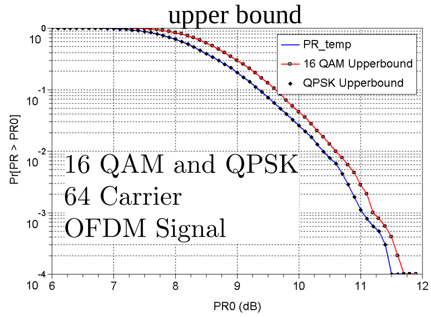
FFT size and modulation type effects

FFT size effect on OFDM upper bound



Upperbound approaches PR_temp when N becomes large

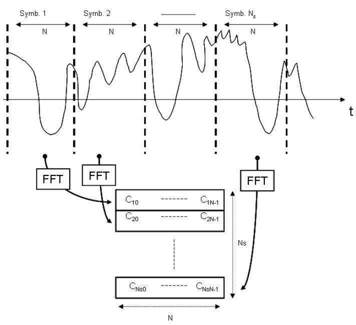
Modulation type effect on OFDM upper bound

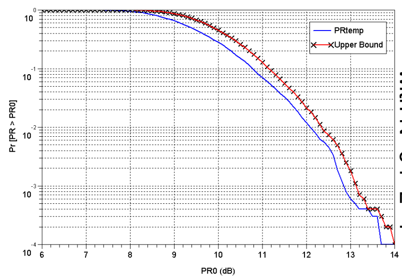


Upperbound = PR_temp for PSK modulations

Frequency Domain PAPR Interpretation (4/6)

- Application to any SWR signals
  - SWR signal is sliced into pieces of FFT size
  - FFT is taken on these pieces to get 'C'
  - Eq. (1) is applied on 'C' and upper bound is obtained





SWR=MC-GMSK+ MC-QPSK+OFDM with N=64 L=4

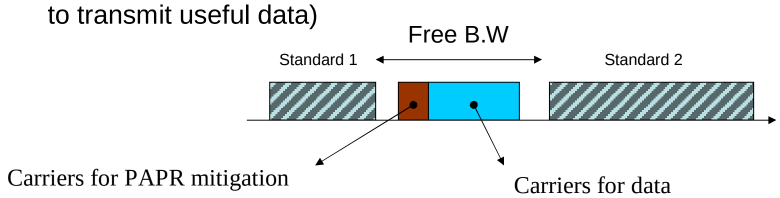
Frequency Domain PAPR Interpretation (5/6)

Supélec

• With the help of this view we can :

• Estimate with individual frequential PAPR the spectrum access influence on global PAPR

•Optimize some of these added carriers for PAPR mitigation (the others to transmit useful data)



Possible methods : TR, Geometrical tone adding method [1]

(1) D Guel, J Palicot, Y Louët, "*A Geometric Method for PAPR Reduction in a Adding Signal in context for OFDM Signals*", International Conference on Digital Signal Processing, DSP 2007, 1-5 July 2007, Cardiff, UK

Frequency Domain PAPR Interpretation- Conclusion (5/6)

Supélec

• Spectrum access in CR should be performed carefully regards to the amplification problems

• PAPR frequency domain view help us for:

• Free spectrum access under PAPR metric constraint.

• PAPR reduction methods based on adding signals in the frequency domain (tone reservation, ...).

• Perspective : Analysis of PAPR behaviour through a communication chain (filtering, ...)

The Execution Plat-form

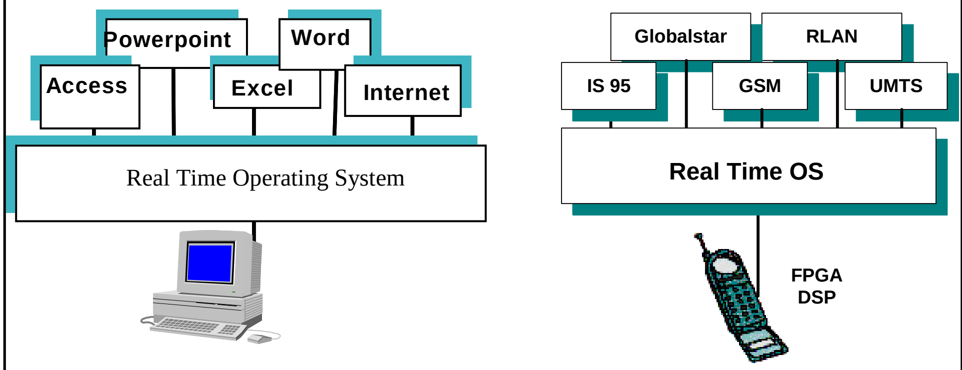
- Parameterisation Techniques
- Partial Reconfiguration of FPGA
- Reconfiguration Management

Parameterization: Generalities

- Resources Optimization
  - Download procedure
    - Software size
    - Download speed
    - Congestion networks
  - Hardware (Digital functions)
    - Runtime speed
    - Consumption
    - Memory size
    - Optimal sharing between the components (FPGA/DSP)

Parameterization: Generalities

PC world analogy :



Parameterization: Generalities

- Co design Optimization
- Reduction of development time
  - Reduction of time to market
  - Decrease the development cost
  - Increase product fiability

Parameterization: Generalities

The execution platform : Parameterization techniques : theoretical approach

We would like to define and optimize a graph containing all the dimensions of our problem :

•Standards

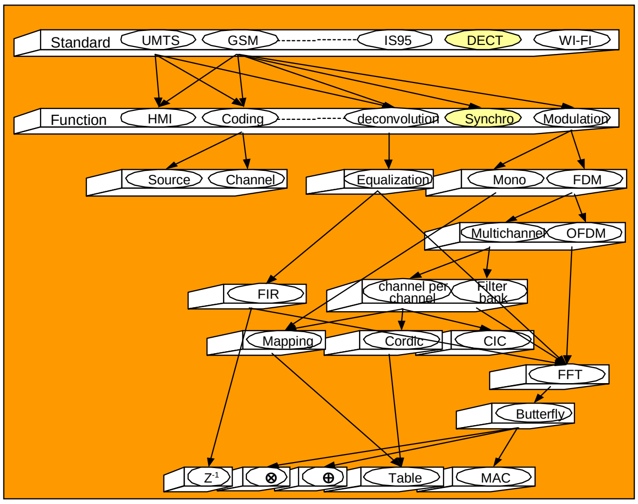
• OSI Layers

•Functions

•Different means to realize these functions

Parameterization: Theoretical approach

Key Question INSTALL or INVOKE[1] ?



[1] **Rodriguez V, Moy C, Palicot J,** ***Install or invoke?: The optimal trade-off between performance and cost in the design of multi-standard reconfigurable radios*****, Wireless Communications and Mobile Computing Journal, Wiley , DOI 10.1002/wcm.487**

Parameterization: Theoretical approach

Optimization of this Graph

The questions are :

Which type of Graph?

Which costs? (Resource, consummation,Operation number, area,….)

Which Cost Functions?

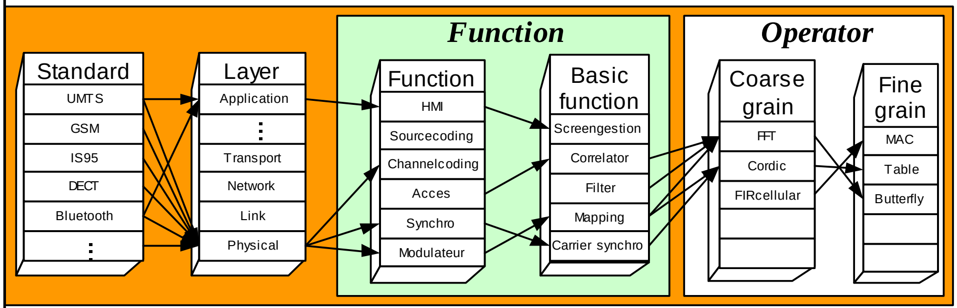
Which optimization algorithm?

Parameterization: Pragmatic Approach : Two Approaches 1/3

- Two very close technical pragmatic approaches
  - Common Functions : For a predefine set of Standards, to research the most common functions.
  - Common Operator[1] : The highest level operator, which is used by the maximum functions of the maximum standards…
    - » To increase the granularity
- This Function or Operator is carried out in hard manner
  - By instance on FPGA or DSP or eventually on ASIC

[1]L.Alaus, J. Palicot, C. Roland, Y. Louët and D. Noguet, " Promising Technique of Parameterization For Reconfigurable Radio, the Common Operators Technique: Fundamentals and Examples", Journal of Signal Processing Systems, Springer, 2009.

Parameterization: Pragmatic Approach : Two Approaches 2/3



Parameterization : The Two approaches

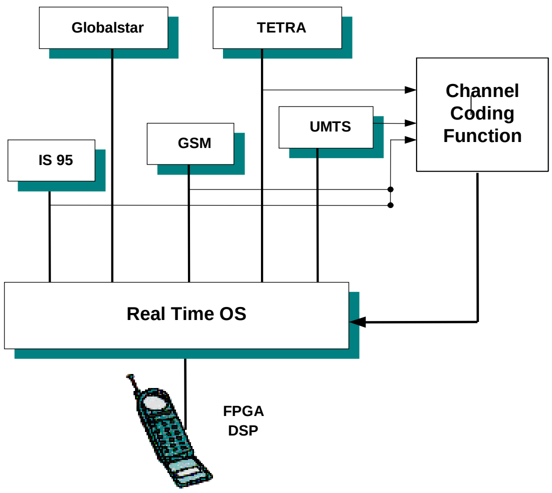
Parameterization: Pragmatic Approach : Two Approaches 3/3

- A function can call (one or several) other functions.
- A function can use (one or several) operators.
- An operator cannot call a function.
  An operator cannot use a function

o If it is a software implementation (DSP), it is more logical to consider it as a function.

o If it is an hardware implementation (FPGA), it is more logical to consider it as a operator.

Common Function



Common Function

- Common Function : an example

  The Channel Decoding[1]

  - Channel coding is now mandatory in every current and future standards .
    - » Studied Systems : GSM, TETRA, TETRAPOL, UTRA;
    - » Several different types of code : convolutionnal codes, turbo codes;
    - » Different types of interleaving.

[1]Arnd-Ragnar Rhiemeier, "Benefits and Limits of Parametrized Channel Coding for Software Radio", 2nd Karlsruhe Worksop on Software Radios, Germany, march 2002.

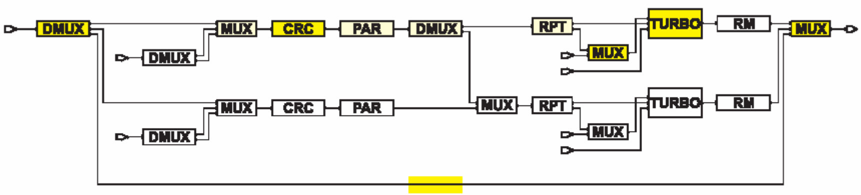
Channel decoding GSM example

CC and CRC D^3+D+1 for TCH/FS

GSM TCH/FS

used

crossed



FFT Operator 1/5

- common Operators :First example

  The FFT Operator[1]

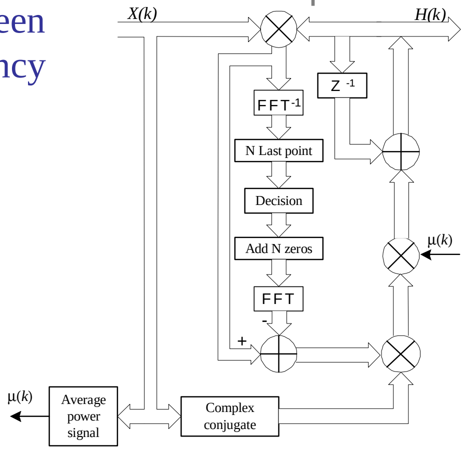
  - Almost all base band functions of current receivers, when they are performed in digital, could be carried out in the frequency domain using the FFT operator.
  - In addition, some former functions done in analog are now performed in digital (DFE functions). Consequently, we show that they also could be done with FFT operator.

[1]J.Palicot, C. Roland, « FFT : a basic function for a reconfigurable receiver », ICT' 2003 , February 2003

FFT Operator 2/5

- Many equalizers have been derived in the Frequency Domain using FFT operator.
  - Classical FLMS et UFLMS
  - SIMO equalizers
  - CMA
  - DFE
  - MIMO

UFLMS equalizer



FFT Operator 3/5

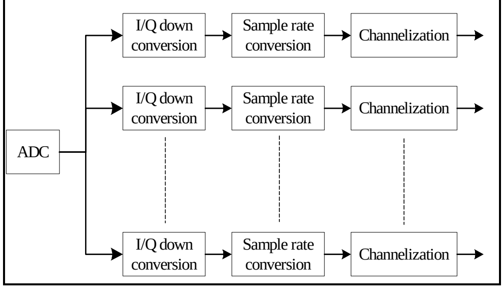
Multicarrier Modulation/Demodulation

- Use by definition orthogonal transform for the modulation and demodulation schemes
- FFT operator is used in standardized systems, which used COFDM modulation, such as : DAB, DVB-T, HiperLAN 2, IEEE 802.11, ADSL…

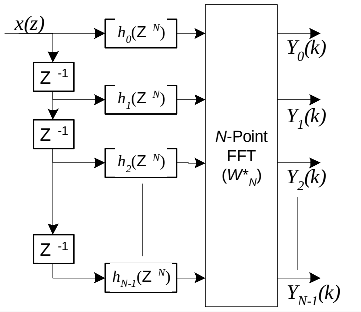
FFT Operator 4/5

Digital Front End FUNCTIONS (Base Station)

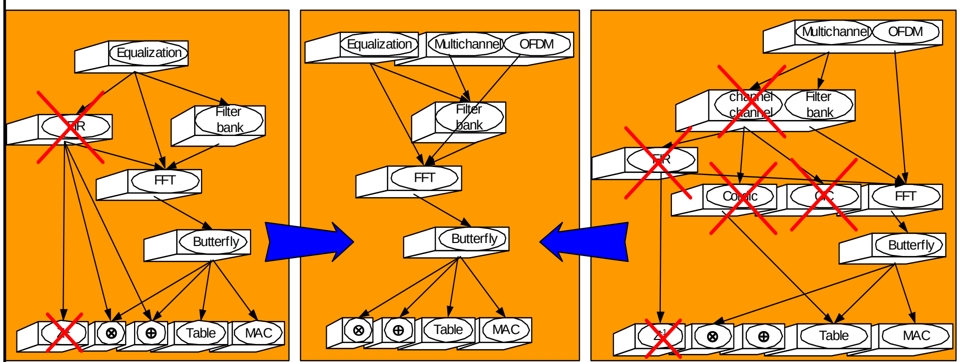
Classical Channel by Channel vision



Multi-channel Vision



FFT Operator - Result 5/5



Partial Reconfiguration of FPGA[1]

• Standards present many functions communalities
• Only some sub-part should be changed during a reconfiguration (standard switching for example,..)
• Partial reconfiguration is an essential feature of SWR systems.
  • This feature has only been reserved to processors until now: changing a sub-part of the executable code of a DSP.

• **We show how this concept of PR may be generalized to the reconfigurable HW world.**

[1] JP Delahaye, C Moy, P Leray, J Palicot, « Managing Dynamic Partial Reconfiguration on Heterogeneous SDR Plaforms »
Outstanding Paper Award SDR Forum 2005

Partial Reconfiguration of FPGA

• Partial reconfigurability allows to selectively change segments of a FPGA functionality during execution time.

• More Flexibility

• Decrease the bit stream

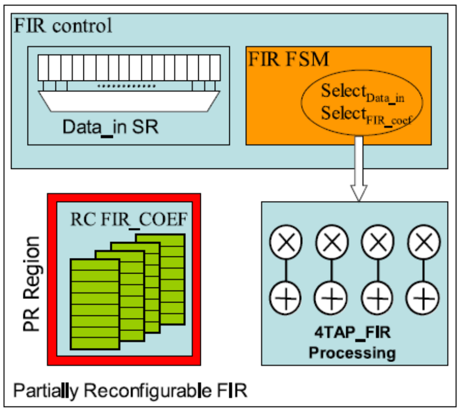
  • Decrease the memory

  • The time to reconfigure

  • The load on a link to download the bitstream

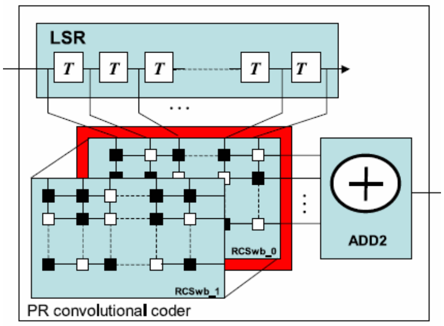
Partial Reconfiguration of FPGA

FIR example
PR of the taps to change the filtering function



Partial Reconfiguration of FPGA

Convolutional coder example
PR of the switching box



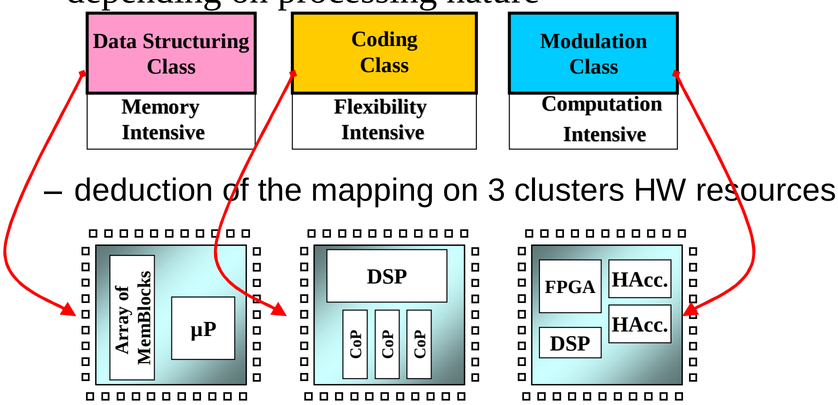
Partial Reconfiguration of FPGA

IP	Bitstream Size	Reconfiguration Time
Fully Reconf. FIR	74.7 kB	1.5 ms
PR FIR	25.7 kB	510 μs
PR Conv. coder	2 kB	40 μs

Some results with PR

Heterogeneous processing units

- Classification of processing functions in 3 classes
  - depending on processing nature
  - deduction of the mapping on 3 clusters HW resources

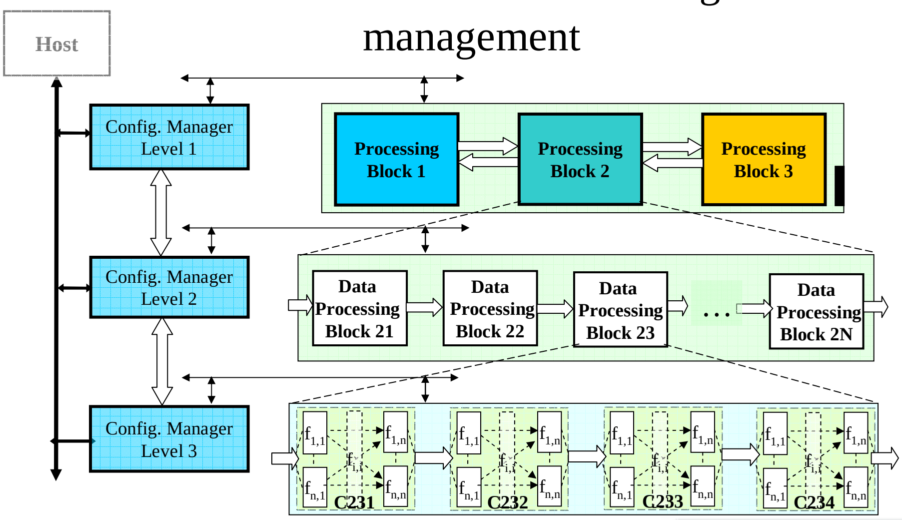


Delahaye JP, Palicot J, Leray P, *A Hierarchical Modeling Approach in Software Defined Radio System Design*, SIPS 2005 , Athènes ,Grèce

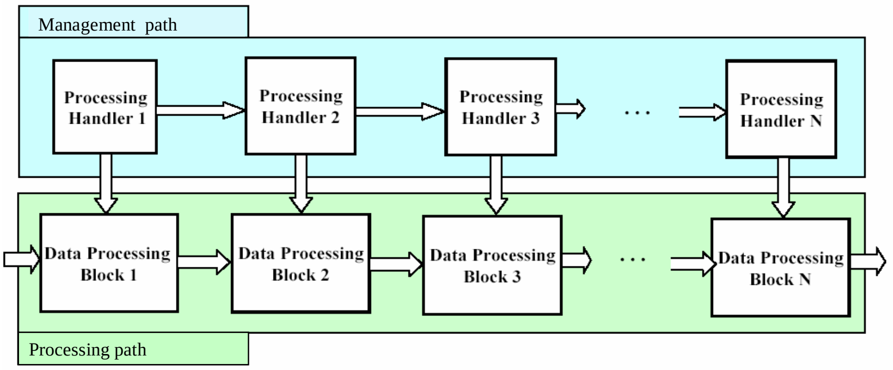
Execution Platform: the reconfiguration management

- **Several contexts:**
  - **Standard**: greatest reconfiguration.
  - **Mode modification**: intra-standard modification.
  - **Performance Improvement , debugging**: small reconfiguration, on the fly, without link break-down.

Execution Platform: the reconfiguration management



Execution Platform: the reconfiguration management



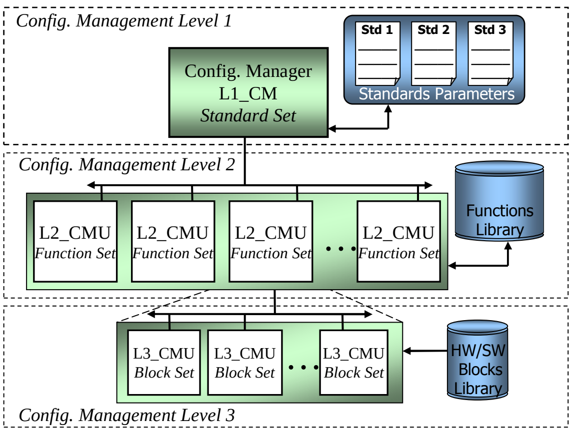
Two paths: one data path and one management path

- Identified constraints for SDR
  - distributed management
  - multi-granularity issue
  - in function of the HW support

L1_CM :
- Global manager
- Standard parameter control
- Dispatches orders to lower layers

L2_CMUs :
- Function Level
- Independent of the HW
- Manages several elementary PB-processing blocks of lower granul.

L3_CMUs :
- Processing blocks configuration
- Embedded very closely to the PB
- Dedicated to the nature of reconfigurable resources



CONCLUSION 1/2

- Impossible to put priority on difficulties and technical challenges because they are too many and fully interconnected.
- These technical challenges are so important than we can conclude

→ ~~SWR~~ not before 10years

- It is also not possible to predict those which will be solved firstly because they are too complex and are studied by different communities.
- SDR (by bypassing AFE and ADC problems) offers now the technology for a beginning of Cognitive Radio.
- From our point of view, sensors problems and high level management problem are inescapable challenges and will occupied many researchers during a lot of years.

CONCLUSION 2/2

- Wireless capacity

Cooper's Law

- X2 every 3 years since one century
  - This gain has been obtained =
    - X 25 using wider spectrum
    - X 5 sharing small channels
    - X 5 improved modulation
    - X 1600 reduced cell sizes

We believe that the next 50 years the improvement will be given by **cognitive radio**

- **Vikram Chandrasekhar and Jeffrey G. Andrews, " Femtocell Networks: A Survey ", arxiv.org/pdf/0803.0952v2.pdf**
- **[1]MS.Alouini and A.J.Goldsmith, "Area Spectral Efficiency of Cellular Mobile Radio Systems", IEEE Tr on Vehicular Technology, vol 48, n°4, pp1047-1066,July 1999.**

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    - 20 PhD students
    - 2 Post- Doc
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    - Jacques.palicot@supelec.fr