Cognitive Radio Networks

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Agenda

- Human Mind
- Cognitive Radio Networks
- Standardization
- Dynamic Frequency Hopping
- Trends
- COST IC 0902
- Reconfigurable Radio Systems

Tasks of a Human Mind

An extract taken from the book:

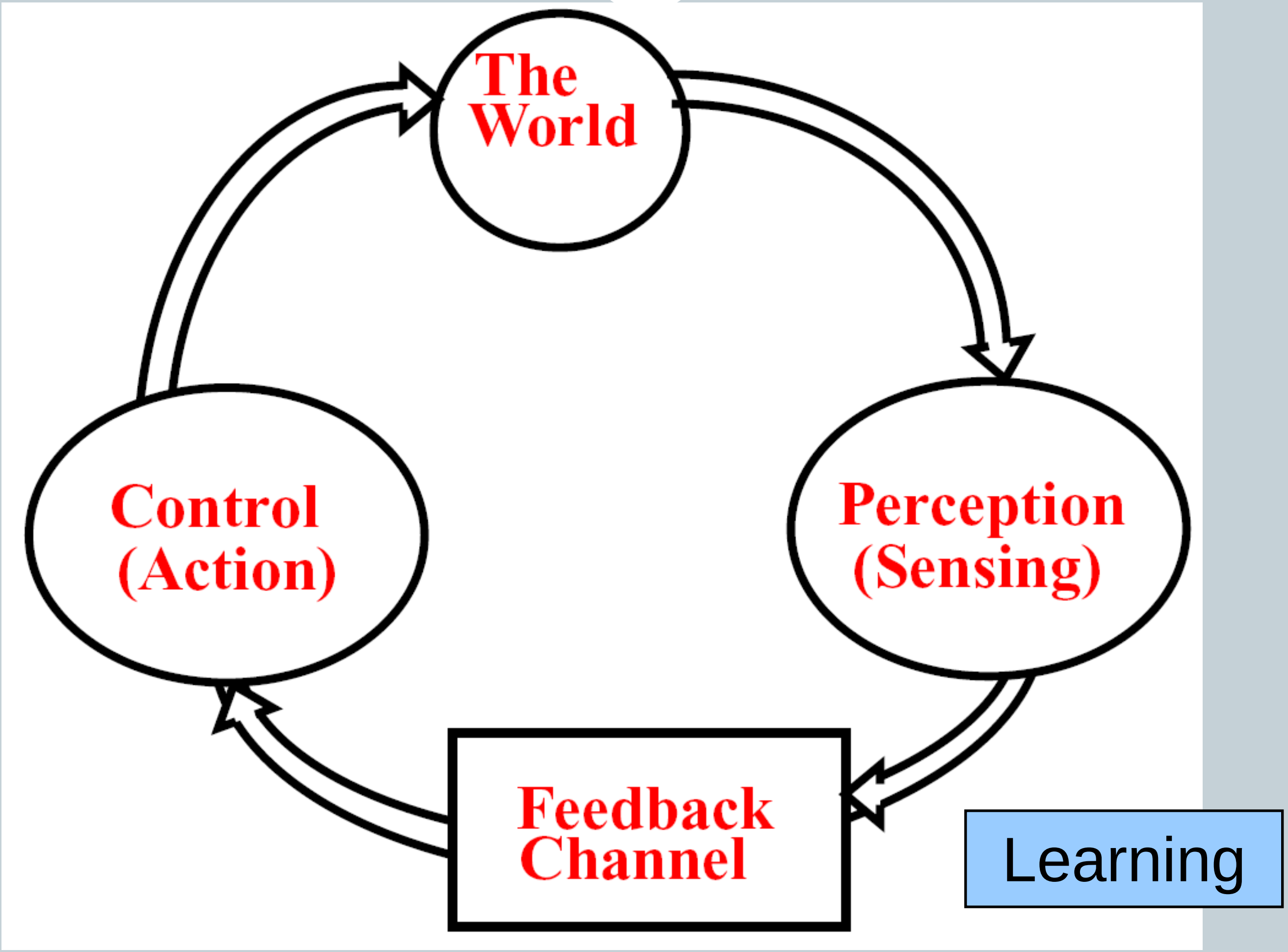
"The Computer and the Mind" by Johnson-Laird

- to perceive the world;
- to learn, to remember, and to control actions;
- to think and create new ideas;
- to control communication with others;
- to create the experience of feelings, intentions, and self-awareness.

Johnson-Laird, a prominent psychologist and linguist, went on to argue that:

Theories of The Mind Should Be Modeled in Computational Terms.

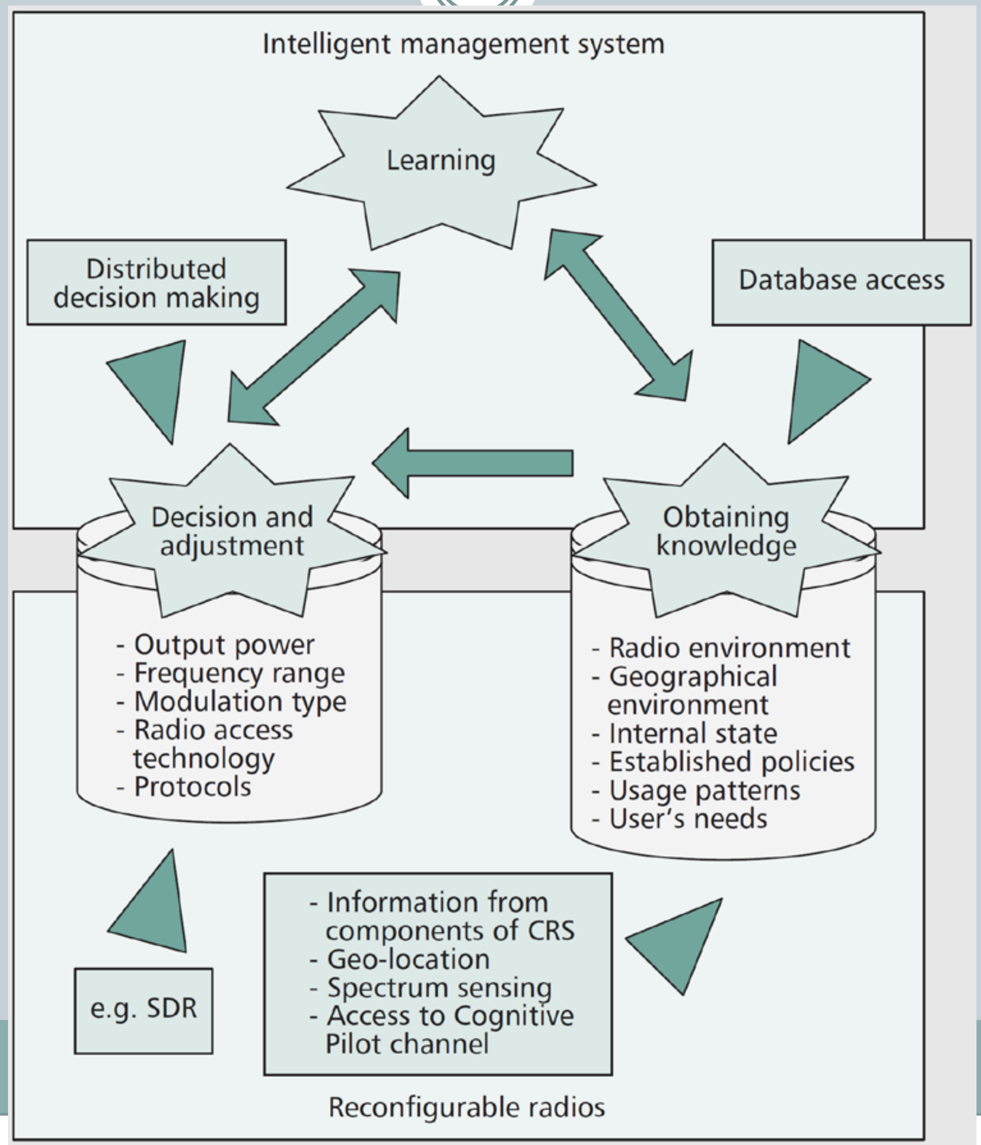
Human Cognitive Cycle



ITU definition of CRS

- A radio system employing technology that allows the system:
- to obtain knowledge of its operational and geographical environment, established policies and its internal state;
- to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives;
- and to learn from the results obtained”

CRS concept

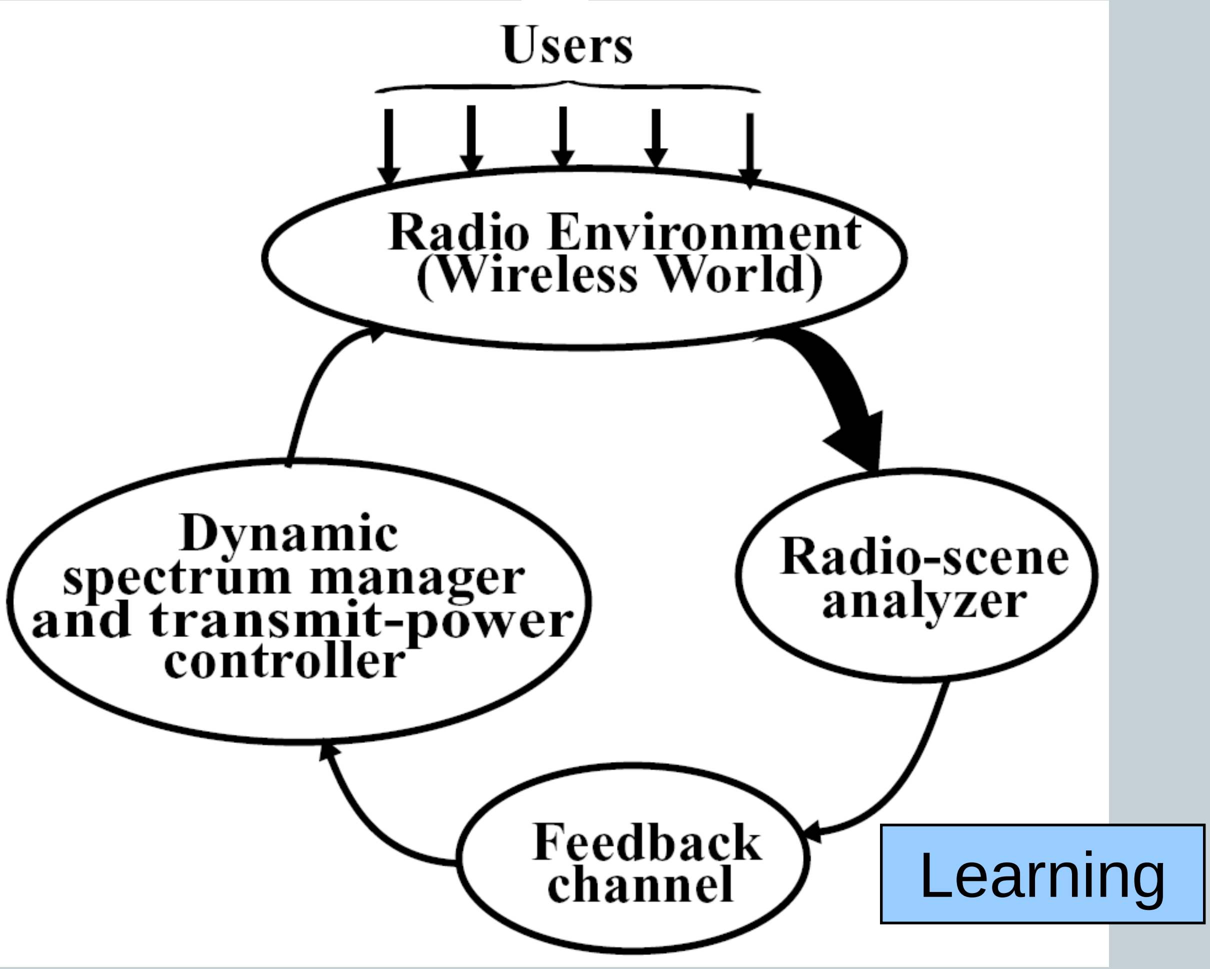


Intelligent management system
Learning
Distributed decision making
Database access
Decision and adjustment
Obtaining knowledge
- Output power
- Frequency range
- Modulation type
- Radio access technology
- Protocols
- Radio environment
- Geographical environment
- Internal state
- Established policies
- Usage patterns
- User's needs
e.g. SDR
- Information from components of CRS
- Geo-location
- Spectrum sensing
- Access to Cognitive Pilot channel
Reconfigurable radios

Comparison of different types of adaptive radio devices

Type of radio	Platform	Reconfiguration and adaptability	Intelligence
Hardware	Hardware	Minimal	None
Software	Hardware/software	Automatic	Minimal
Adaptive	Hardware/software	Automatic/predefined	Minimal/none
Reconfigurable	Hardware/software	Manual/predefined	Minimal/none
Policy-based	Hardware/software	Manual (database)/automatic	Minimal/none
Cognitive	Hardware/software	Full	Artificial/machine learning
Intelligent	Hardware/software	Full	Machine learning/use of prediction for decision

Basic signal-processing cycle,
as seen by a single user (transceiver)



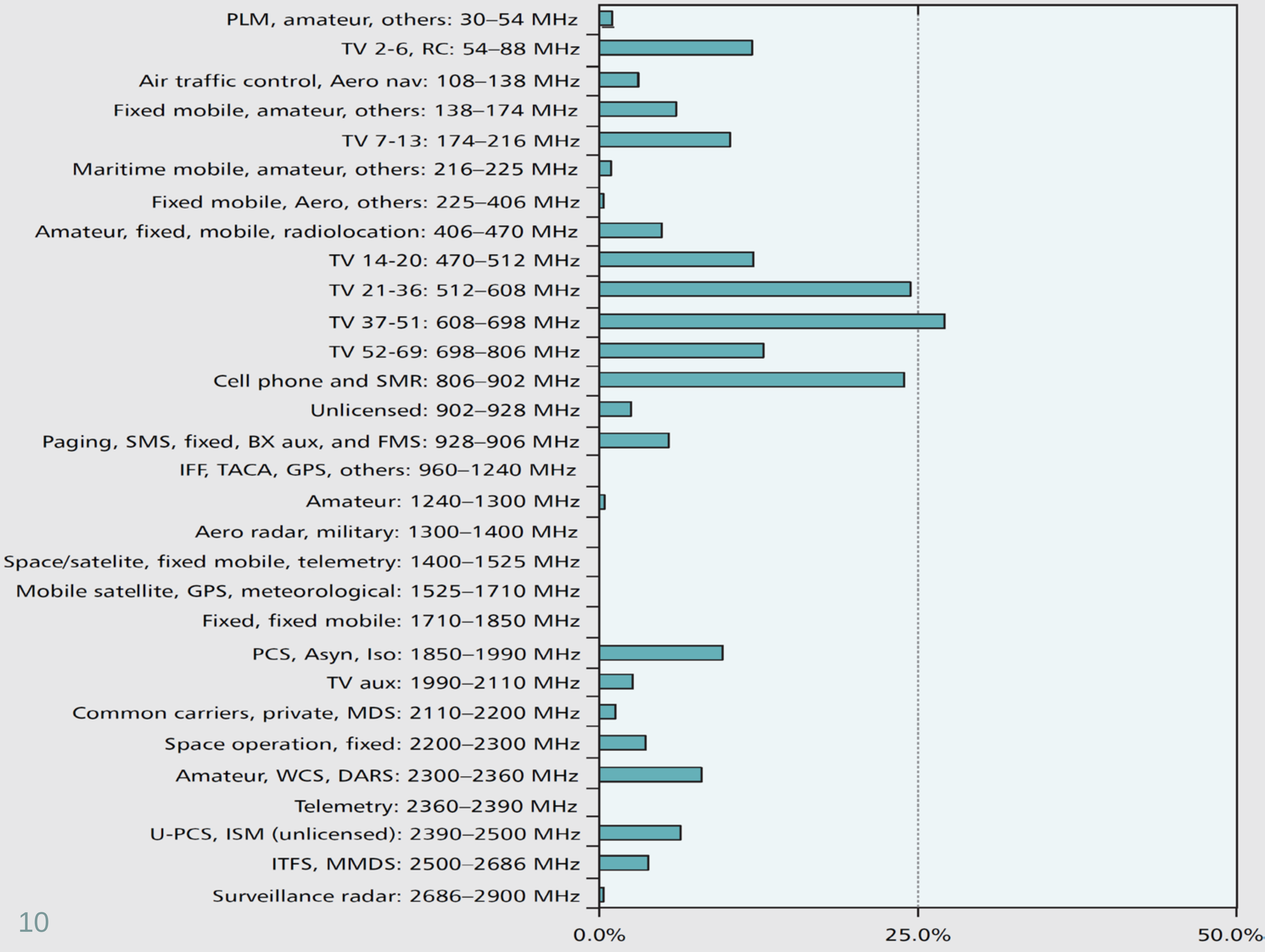
Motivation Behind Cognitive Radio

- Significant underutilization of the radio spectrum
- Basically Cognitive Radio solves the spectrum underutilization problem in a pair of ways:

(i) Sense the radio environment to detect spectrum holes in terms of both time and location.

(ii) Control employment of the spectrum holes by secondary users efficiently, subject to the constraint:

The total power in each spectrum hole does not exceed a prescribed limit.


PLM, amateur, others: 30–54 MHz
TV 2-6, RC: 54–88 MHz
Air traffic control, Aero nav: 108–138 MHz
Fixed mobile, amateur, others: 138–174 MHz
TV 7-13: 174–216 MHz
Maritime mobile, amateur, others: 216–225 MHz
Fixed mobile, Aero, others: 225–406 MHz
Amateur, fixed, mobile, radiolocation: 406–470 MHz
TV 14-20: 470–512 MHz
TV 21-36: 512–608 MHz
TV 37-51: 608–698 MHz
TV 52-69: 698–806 MHz
Cell phone and SMR: 806–902 MHz
Unlicensed: 902–928 MHz
Paging, SMS, fixed, BX aux, and FMS: 928–906 MHz
IFF, TACA, GPS, others: 960–1240 MHz
Amateur: 1240–1300 MHz
Aero radar, military: 1300–1400 MHz
Space/satelite, fixed mobile, telemetry: 1400–1525 MHz
Mobile satellite, GPS, meteorological: 1525–1710 MHz
Fixed, fixed mobile: 1710–1850 MHz
PCS, Asyn, Iso: 1850–1990 MHz
TV aux: 1990–2110 MHz
Common carriers, private, MDS: 2110–2200 MHz
Space operation, fixed: 2200–2300 MHz
Amateur, WCS, DARS: 2300–2360 MHz
Telemetry: 2360–2390 MHz
U-PCS, ISM (unlicensed): 2390–2500 MHz
ITFS, MMDS: 2500–2686 MHz
Surveillance radar: 2686–2900 MHz
0.0%
25.0%
50.0%

Major Functional Blocks of Cognitive Radio

1. **Spectrum sensing**: Detect spectrum holes, estimate their power contents.
2. **Predictive modeling**: Predict availability of spectrum hole is employment by secondary user.
3. **Transmit- power control**: Maximize data rate of each user subject to power constraints
4. **Dynamic spectrum management**: Control distribution of spectrum holes fairly among secondary users
5. **Packet routing**: Route the packets across the network efficiently

IC0902

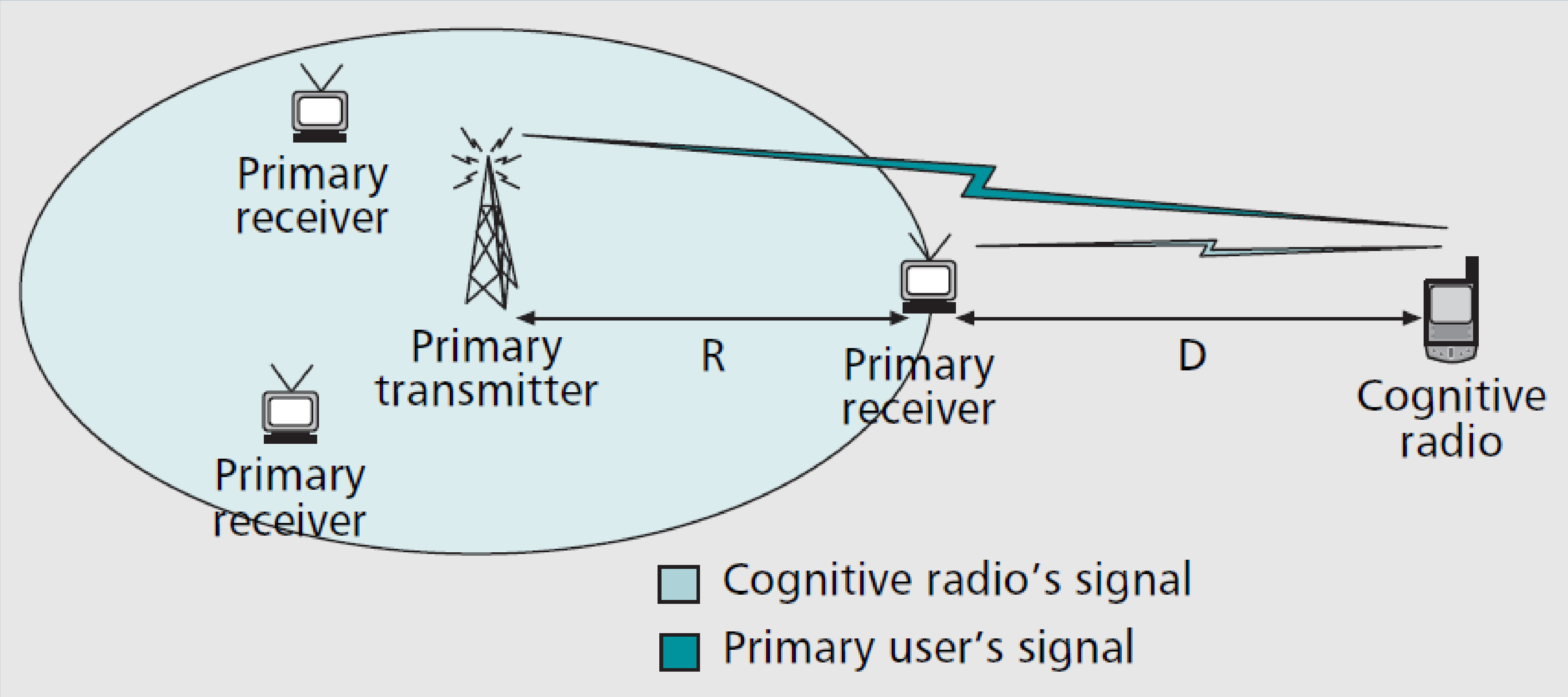
Classification of white space identification methods

	Infrastructure cost	Legacy compatibility	Transceiver complexity	Positioning	Internet connection	Continuous monitoring	Standardized channel
Database registry	High		Low	X	X		
Beacon signals	High		Low	X			X
Spectrum sensing	Low	X	High			X	

Reactive vs. Proactive Sensing

- Spectrum sensing schemes may be categorized as reactive and proactive, depending on the way they *search* for white spaces.
- Reactive schemes operate on an on-demand basis where a cognitive user starts to sense the spectrum only when it has some data to transmit.
- Proactive schemes aim at minimizing the delay incurred by cognitive users in finding an idle band by maintaining a list of one or more licensed bands currently available for opportunistic access through periodic sensing of the spectrum.

Interference range of a cognitive radio



Cooperative Spectrum Sensing

- Under **fading or shadowing**, a cognitive radio requires higher detection sensitivity in order to overcome the uncertainty introduced by channel randomness.
- Multipath fading effects vary significantly depending on the **receiver's location**.
- The uncertainty may be mitigated by allowing the users to **share** their **sensing results** and **cooperatively decide** on the licensed spectrum occupancy.
- The diversity gain achieved through **cooperative spectrum sensing improves the overall detection sensitivity**.
- The improved sensitivity comes at the cost of **additional communication overhead**.
- Local measurements should be collected at a **band manager** to be processed into a decision regarding the occupancy state of the primary band.
- This **decision should be broadcast** to all users of the secondary system.
- A **control channel** is needed to enable the exchange of information between the cooperating cognitive radios and the band manager.
- The band manager then **declares a white space only if none of the cooperating users has detected a primary signal**.

Dynamic-Spectrum Management

Time- and Location-dependent Optimization Problem

- **Centralized Approach**

(i) Centre for collecting radio-scene information on all users

(ii) *Globally optimal* solution for the problem

(iii) *Impractical* for two main reasons:

- **High complexity**
- **Non-scalability**

Dynamic Spectrum Management (cont.)

- Decentralized Approach:
  - Utilization of neurobiological principles of self-organization, with emphasis on learning.
  - Emphasis on cognitive radio information on a local neighborhood basis.
  - Complexity is proportional to the user-density, and therefore scalable to any size.
  - Provision of a stable solution with less complexity.
  - Suboptimal but satisfactory solution.

IEEE 802.22

- Cognitive radio - an enabling technology that allows unlicensed radio transmitters to operate in the licensed bands at locations where that spectrum is temporally not in use.
- IEEE 802.22 - The first wireless standard based on Cognitive Radios

Other Standards

TV band NPRM released by the FCC

- In the US, TV stations operate from channels 2 to 69 in the VHF and UHF portion of the radio spectrum.
- All these channels are 6 MHz wide, and span from 54-72 MHz, 76-88 MHz, 174-216 MHz, and 470-806 MHz.
- On June 12, 2009 in United States full power TV stations were required to switch to digital transmission and operate only between 54−698 MHz.

FCC NPRM

(Federal Communications Commission Notice of Proposed Rulemaking)

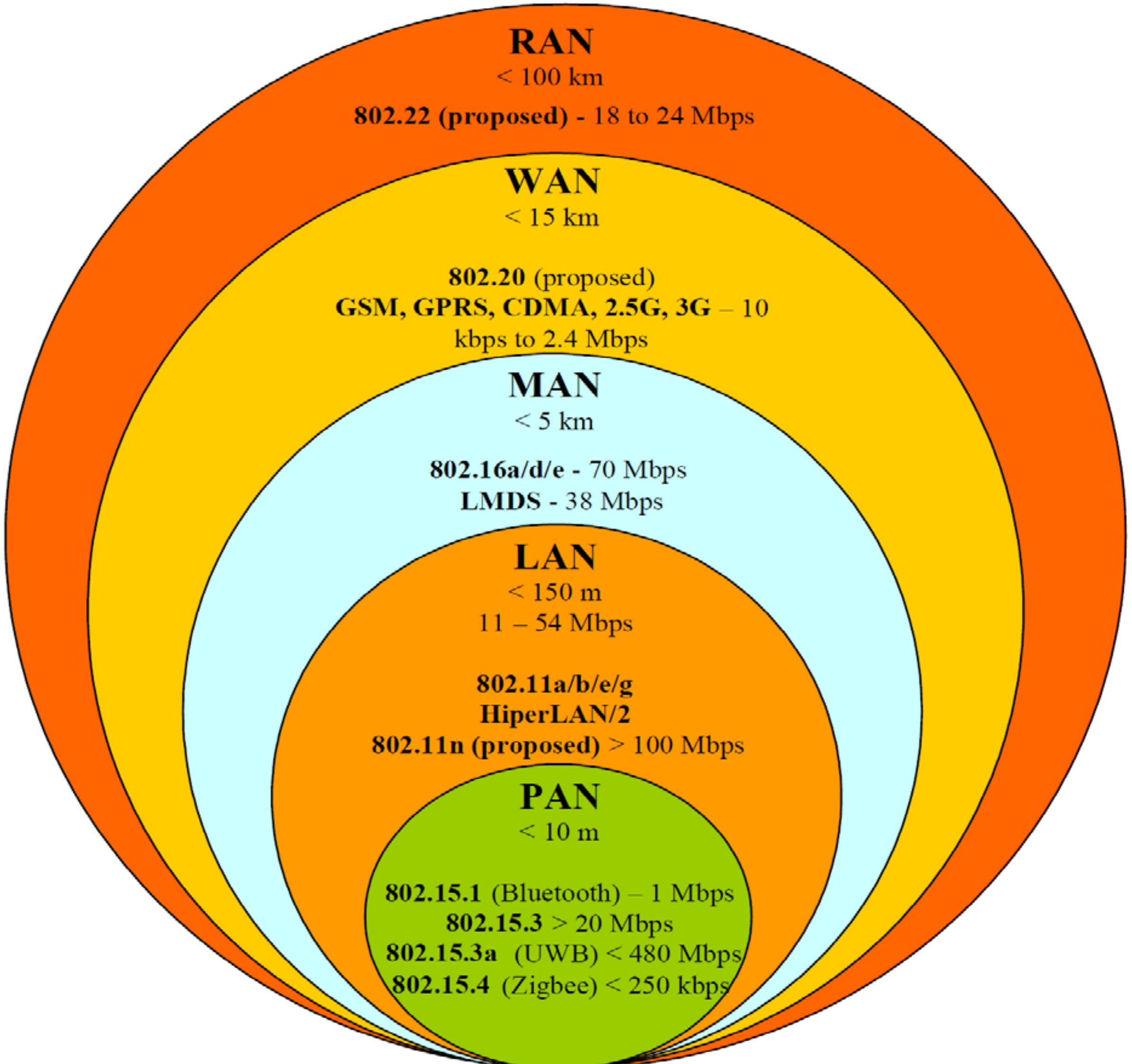
- Open the spectrum allocated to the TV service for unlicensed operation based on CRs.
- In addition to the TV service, also called primary service, there other services such as
  - wireless microphones are also allowed by FCC to operate on vacant TV channels on a non-interfering basis (please refer to Part 74 of the FCC rules)
  - Private Land and Commercial Mobile Radio Services (PLMRS/CMRS) including Public Safety (please refer to Part 90 of the FCC rules)

Medical Body Area Networks -**MBANS**

- Frequency band 2360–2400MHz for MBANS on a secondary basis was initially made in the US by GE in 2007, followed by a NPRM issued by the FCC in 2009.
- The principal incumbent in US is Aeronautical Mobile Telemetry (AMT), (2360–2390 MHz)
- Allow MBAN devices as secondary users to coexist with the primary ATS user, without either creating interference to or being subject to interference from AMT services.
- Techniques to protect AMT from interference while maintaining the quality of service required for the MBANS:
  - Interference mitigation mechanisms, such as Listen-Before-Transmit and Adaptive Frequency Selection (LBT/AFS).
  - The proposed transmit power for MBANS is quite low (1 mW in 2360–2390 MHz and 20 mW in 2390–2400 MHz),

Wireless Regional Area Network (WRAN)

- Regional
- Wide
- Metropolitan
- Local
- Personal



Requirements

- WRAN operations must satisfy two apparently conflicting requirements:
- assure the quality of service (QoS) satisfaction for WRAN services

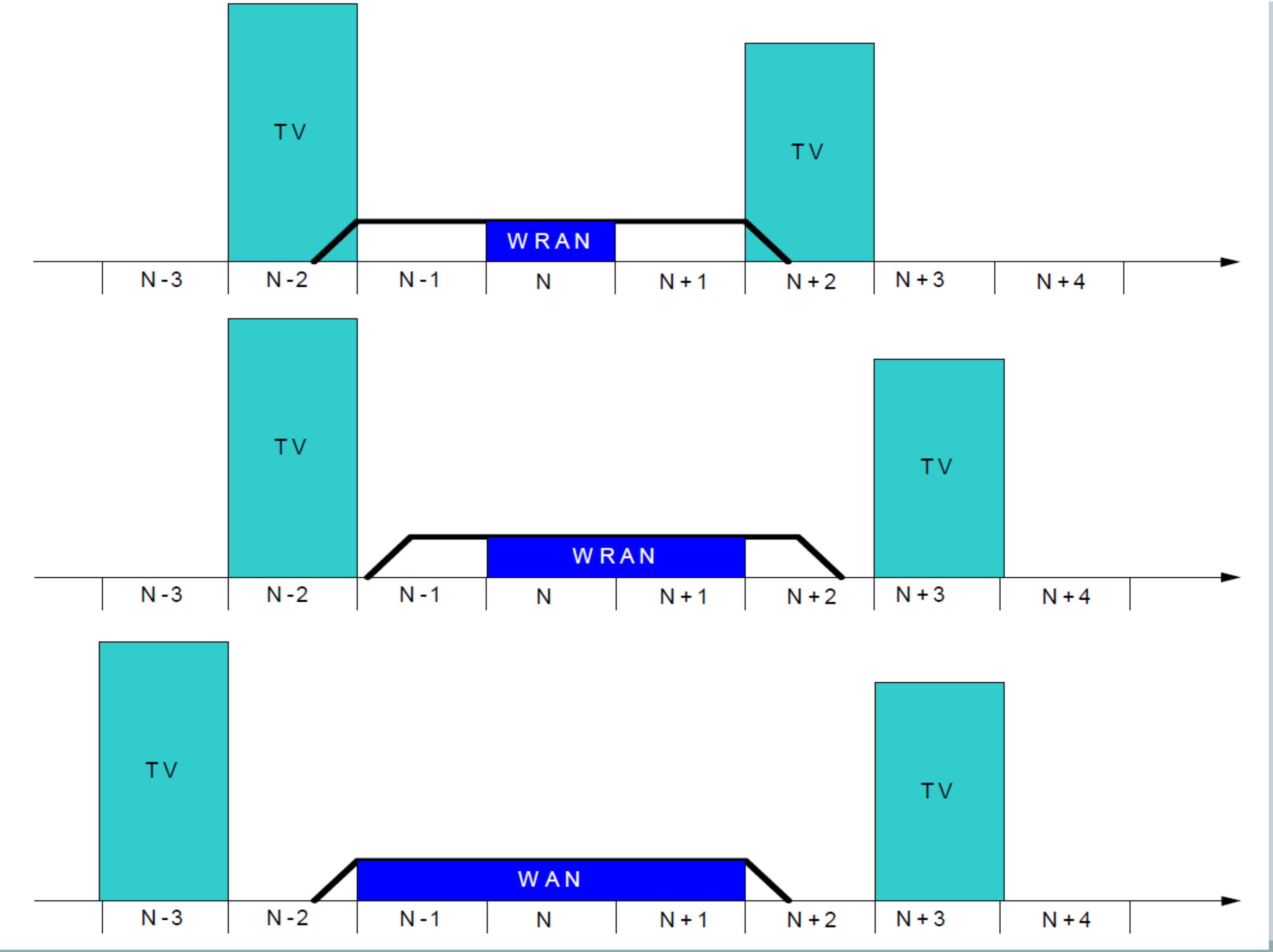
while providing

- reliable and timely spectrum sensing for guaranteeing the licensed user protection.

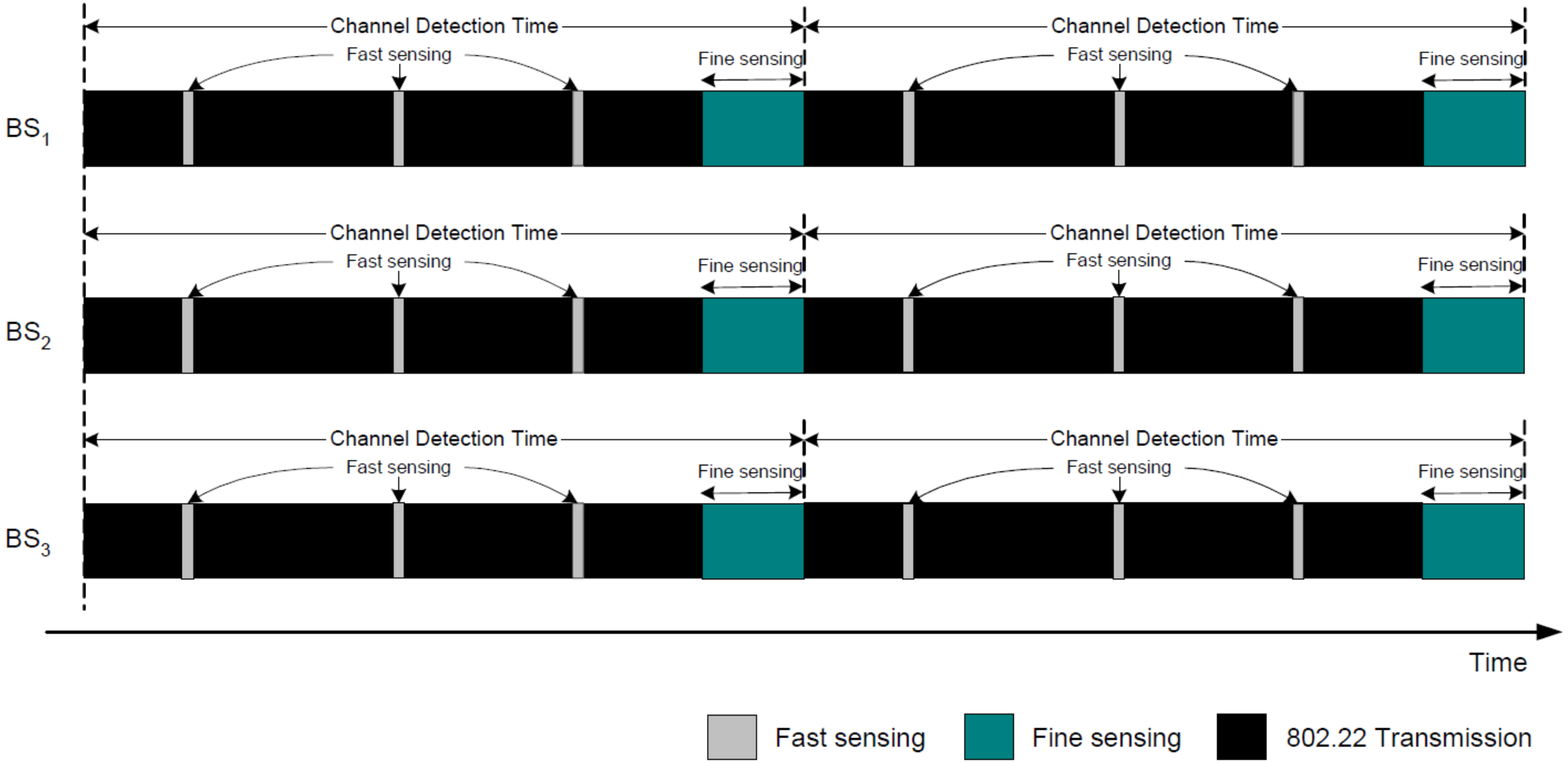
Non-hopping mode

- A channel that is to be sensed cannot be used for data transmission.
- A WRAN cell operating consistently on a single channel must interrupt data transmission every two seconds for sensing and continue to transmit on that channel only if no incumbent was detected.
- Periodic interruptions of data transmission, decrease the system throughput and can significantly impair the QoS (e.g., an interruption of more than 20 ms usually is harmful for voice transmission).

Channel bonding scheme illustrating 1 (top), two (middle), and three TV channels



Two-stage quiet period mechanism



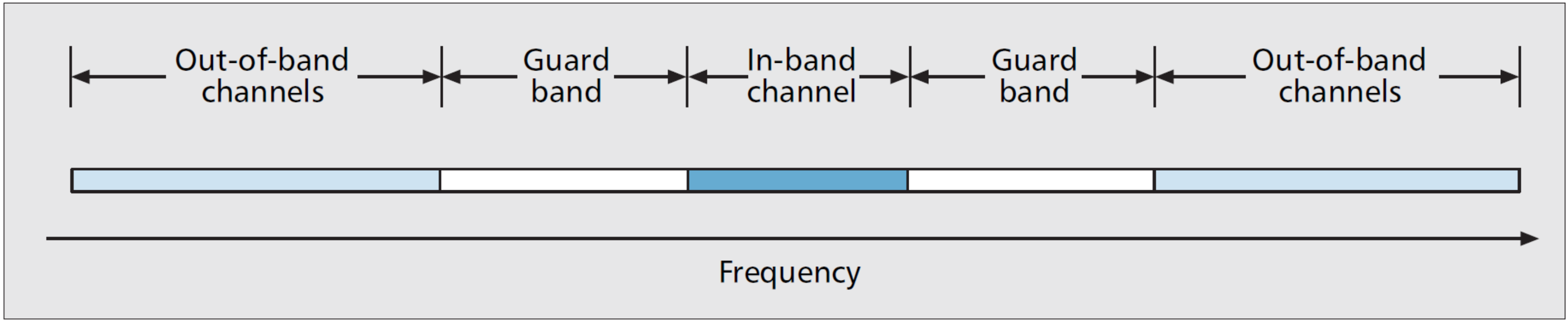
Dynamic Frequency Selection (DFS) for the 5 GHz band

Parameter	Value for Wireless Microphones	Value for TV Broadcasting
Channel Availability Check Time	30 sec	30 sec
Non-Occupancy Period	10 minutes	10 minutes
Channel Detection Time	≤ 2 sec	≤ 2 sec
Channel Setup Time	2 sec	2 sec
Channel Opening Transmission Time (Aggregate transmission time)	100 msec	100 msec
Channel Move Time (In-service monitoring)	2 sec	2 sec
Channel Closing Transmission Time (Aggregate transmission time)	100 msec	100 msec
Interference Detection Threshold	-107 dBm	-116 dBm

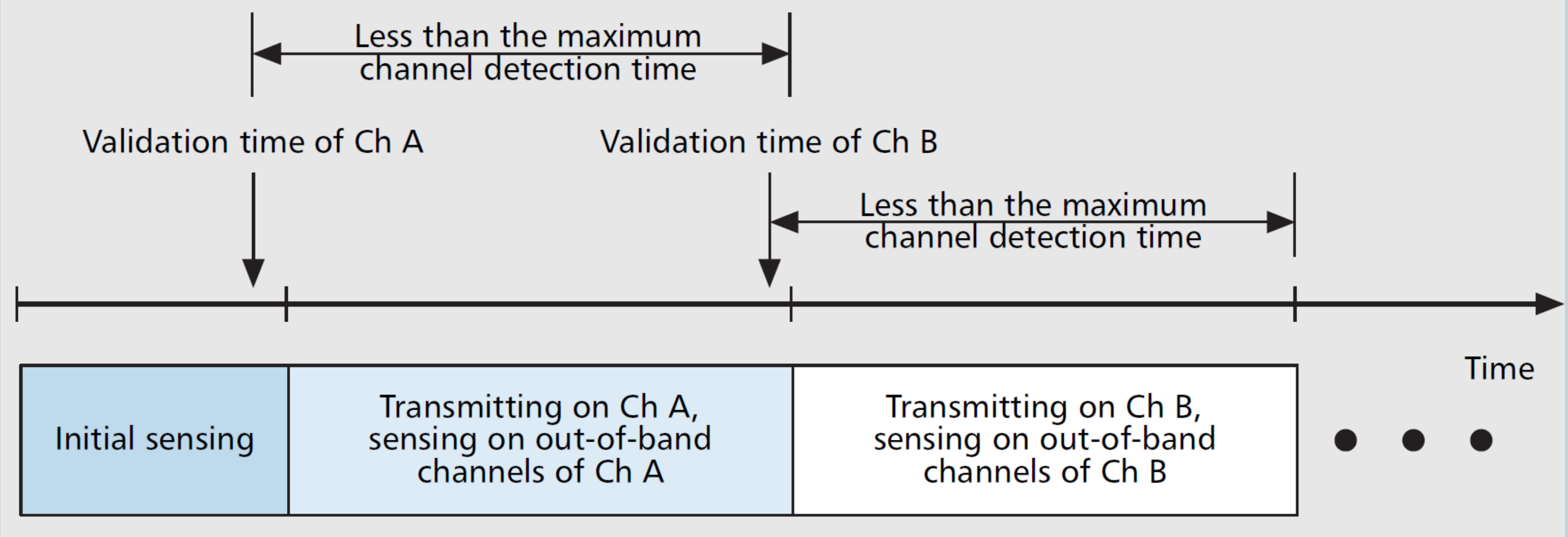
Dynamic frequency hopping (DFH)

- A WRAN cell hops over a set of channels.
- **During operation on a working channel, sensing is performed in parallel on the intended next working channels.**
- After two seconds, a channel switch takes place: one of the intended next working channels becomes the new working channel; the channel previously used is vacated.
- **No interruption is required for sensing** any longer.
- Efficient frequency usage and mutual interference-free spectrum sensing can only be achieved if <u>multiple</u> neighboring WRAN <u>cells</u> operating in the DFH mode <u>coordinate their hopping</u> behavior.

Simultaneous Sensing and Data Transmissions (SSDT) - frequency



Simultaneous Sensing and Data Transmissions (SSDT) - time



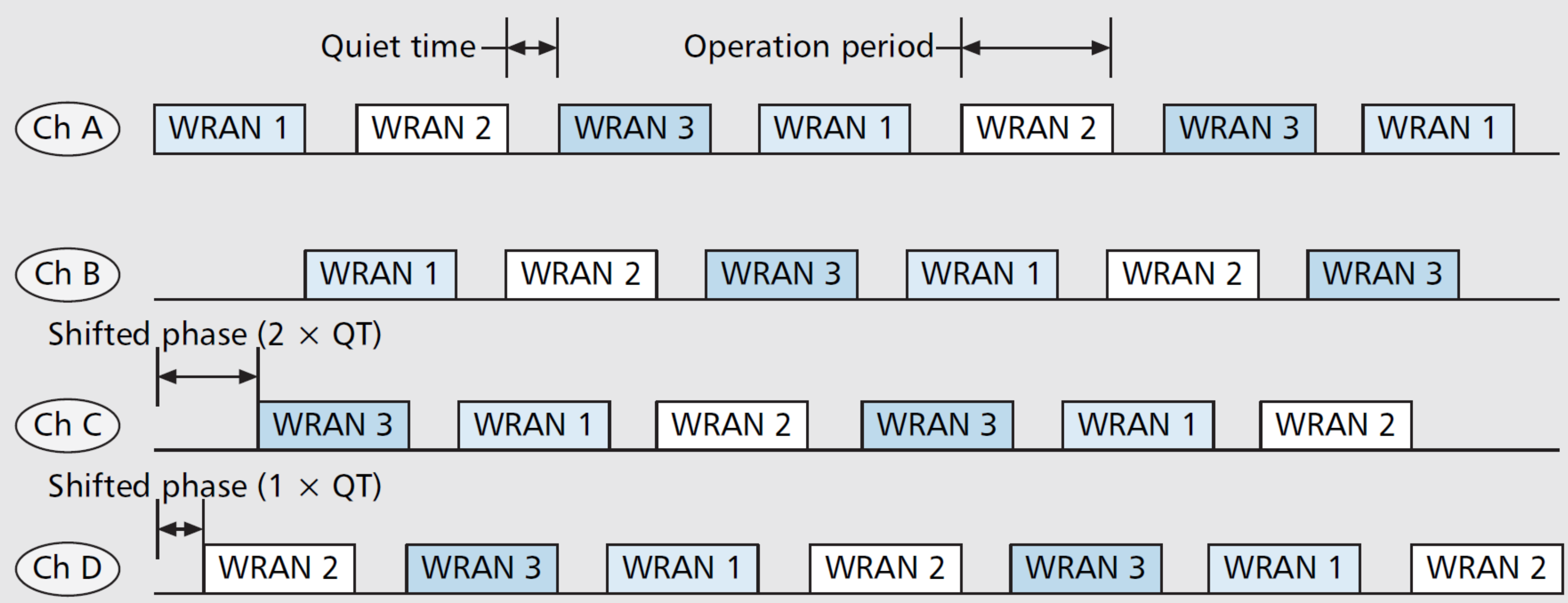
Dynamic Frequency Hopping Communities

- DFHC is a non-empty set of neighboring WRAN cells following a common protocol that supports a coordinated DFH operation to ensure mutual interference-free channel sensing and to minimize the channel usage, applying the DFH phase-shifting
- **A DFHC has one leader and some community members**
- The DFHC leader is responsible for decisions about community membership, calculating the hopping patterns for all members and distributing this information within the community.
- Members provide the leader with their neighborhood and channel availability information, that is, information about their sensing results and observed channel usage of the neighboring WRAN cells.

DFHC Requirements

- Community members can communicate with the community leader
- Communication management channel (CMC)
- Each community member can perform the SSDT operation as described previously.
- Community members have reasonably synchronized clocks (up to a given accuracy).
- The community members share a joint notion of a QT of a channel X — a time period during which no community member is allowed to transmit on that channel.

Phase-shifting DFH operation



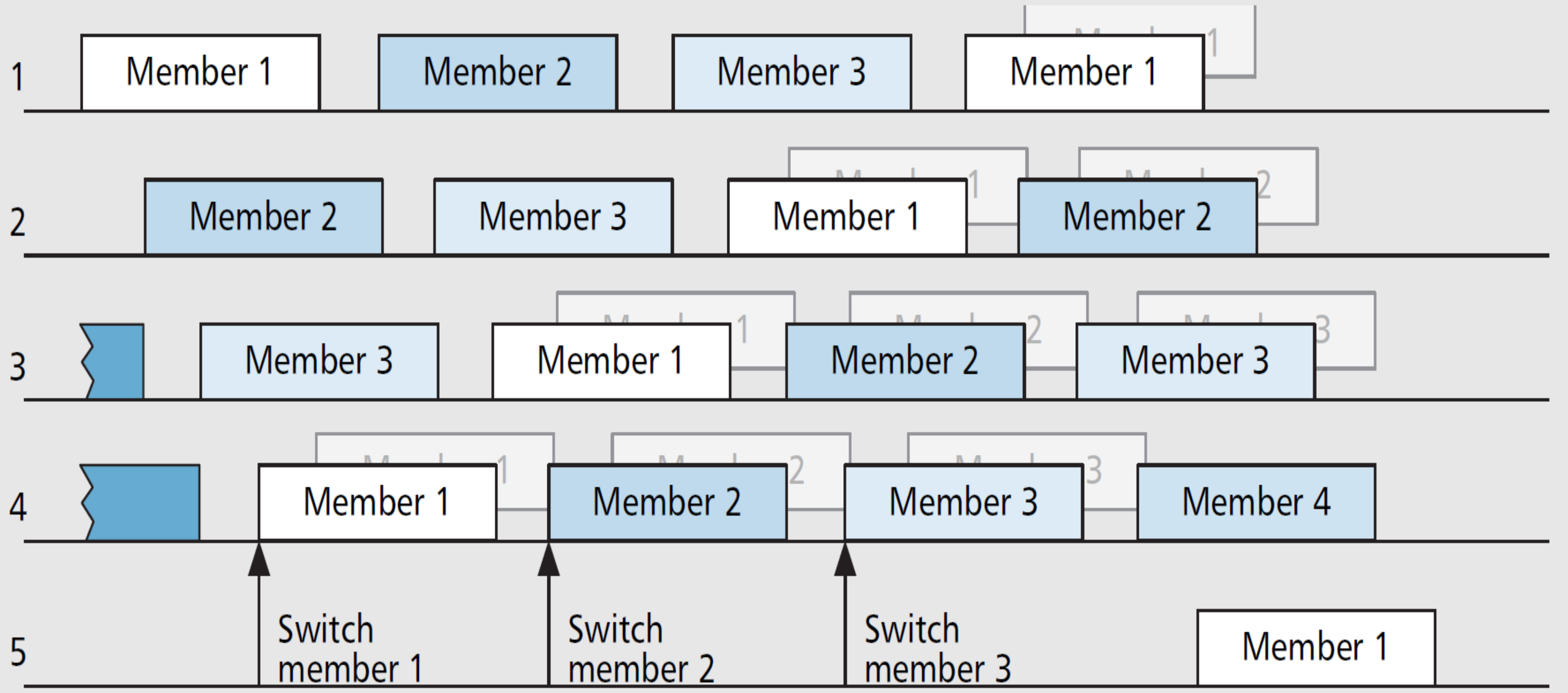
DFHC CREATION

- Community leader selection.
  - The community leader of a DFHC is defined as a BS with the highest priority value (and the smallest MAC address within equal priorities).
  - Each BS considered to fulfill this condition within its neighborhood declares itself a DFHC leader.
  - The declared leader selects a set of hopping channels and broadcasts its leadership using leader announcement (LDRA) messages on the CMC that contains a list of community members and the selected hopping channels with the hopping pattern of the community.
- Member addition
  - Upon receiving LDRA messages from (possibly multiple) leaders, a BS can decide to join one of the advertised communities.
  - To join a community, a BS transmits a membership request message (MBRA) on the community's CMC. An MBRA message contains the targeted community leader's identification and the neighborhood and channel availability information of the requesting BS.
  - Upon receiving the MBRA, the leader decides whether to accept or reject the joining request and sends an acknowledgement containing the decision.

DFHC Maintenance

- Each channel-hopping pattern calculated and distributed by the community leader has a lifetime.
- The leader periodically renews the hopping pattern by broadcasting an LDRA.
- The neighborhood and channel availability information of a community is updated by all members that perform spectrum sensing, tracks BSANN messages from neighboring cells, and reports to the leader by sending MBRA messages.
- The leader recalculates the channel-hopping pattern for the community based on the received MBRA messages.

Sequential switching: Add a new member



DFHC Coexistence

- In a large network of WRAN cells, multiple communities might exist and must coexist.
- A distributed process following appearing/disappearing of cells, as well as changes of their connectivity
- Mechanisms to shift cells between communities and to split and merge communities.
- Rearrangements of established communities might help in:
  - Reducing total number of channels used.
  - Resolving channel usage conflicts among communities.
  - Reducing communication overhead for community management.

Trends

- CR importance
- CR acceptance
- CR standardization:
  - ITU
  - IEEE
    - 802
    - IEEE DySPAN Standards Committee (DySPAN-SC)
      Formerly IEEE Standards Coordinating Committee 41 (SCC41)
  - ETSI
  - ECMA - **European Computer Manufacturers Association** (Information Communication Technology (ICT) and Consumer Electronics (CE)).

IC0902

Thank you for the attention

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European COST program IC0902

- Coordinate networks research on cognitive radio
- Integrates cognitive radio projects of a wide-range of expertise, from hardware to applications
- over 150 academic and industrial partners
- over 30 countries.
- 2010-2013
- Meetings, workshops 3 time per year
- Dr. Arie Reichman was nominated as a management committee member
- http://newyork.ing.uniroma1.it/IC0902/

- Integrating the cognitive concept across all layers of system architecture
- Global optimization process
- Joint optimization of link adaptation
  - spectrum sensing
  - resource allocation
  - selection between multiple networks
- Algorithms and protocols for all layers of the communication
- Interaction between cognitive network nodes
  - Standard interfaces
  - Common reference language

COST IC0902 Main Activities

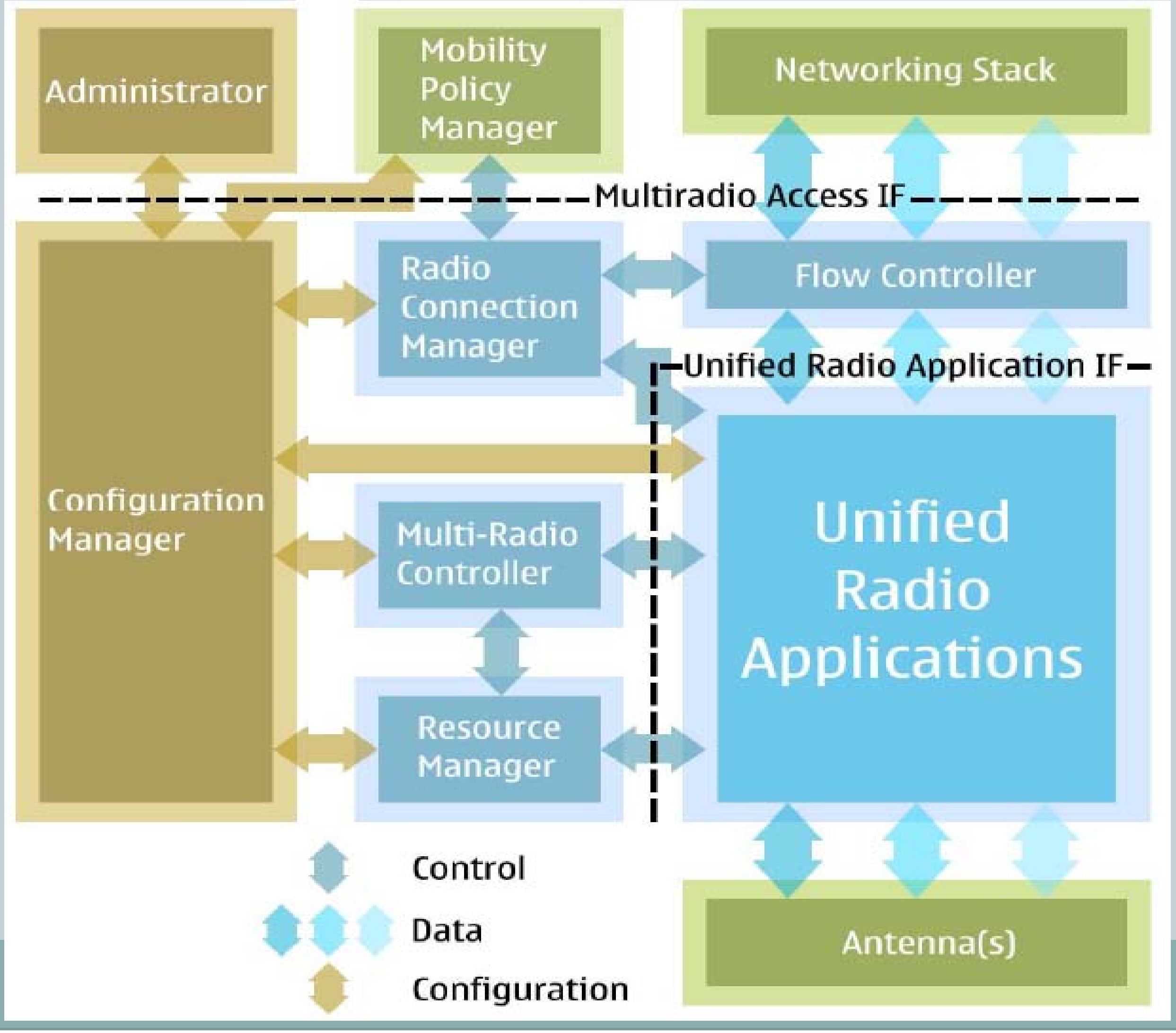
1. Cognitive algorithms for adaptation and configuration of a **single link** according to the status of external environment
2. Cooperation-based cognitive algorithms, that take advantage of information exchange at a **local level**
3. **Network-wide** mechanisms for enabling the cognitive approach
4. Mechanisms for **intersystem** coexistence and cooperation.
5. Cross-layer cognitive **engine**

Reconfigurable Radio Systems (RRS)

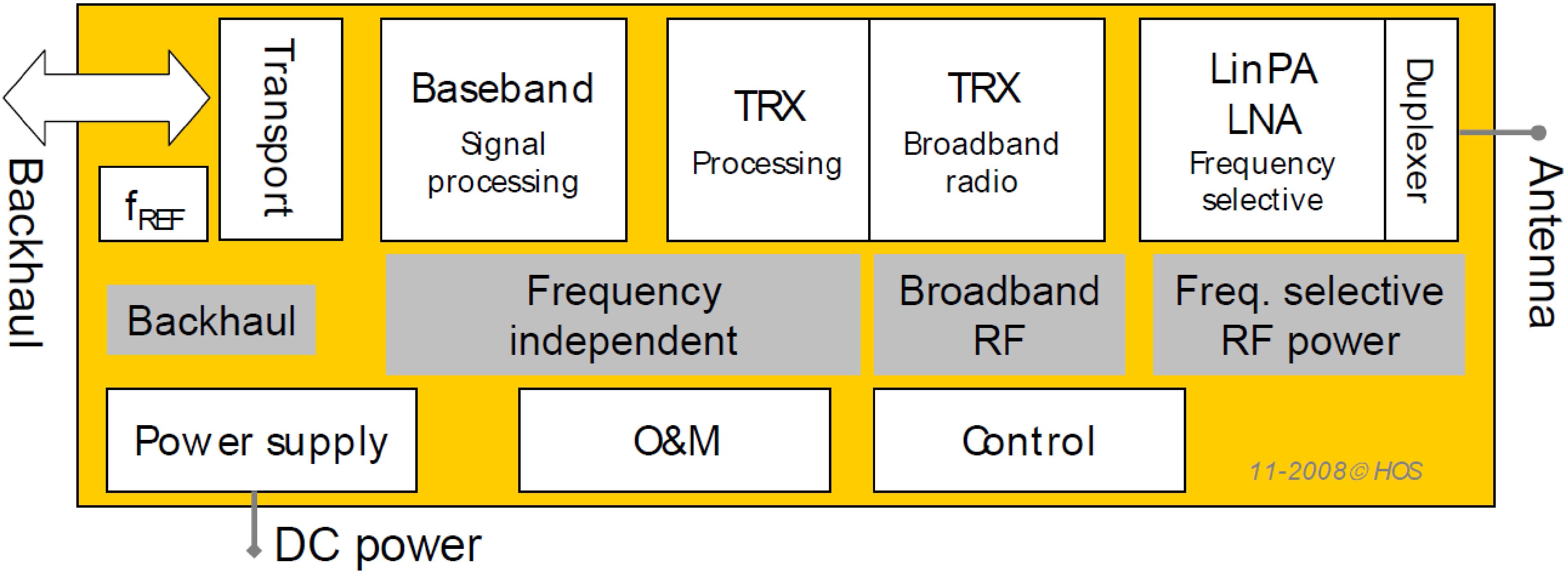
RRS ETSI documents

- ETSI TR 102 680: "SDR Reference Architecture for Mobile Device".
- ETSI TR 102 681: "Radio Base Station (RBS) Software Defined Radio (SDR) status, implementations and costs aspects, including future possibilities".
- ETSI TR 102 682: "Functional Architecture for the management and control of Reconfigurable Radio Systems".
- ETSI TR 102 683: "Cognitive Pilot Channel".
- ETSI TR 102 745: "User requirements for Public Safety".
- ETSI TR 102 838: " Summary of feasibility studies and potential standardization topics".

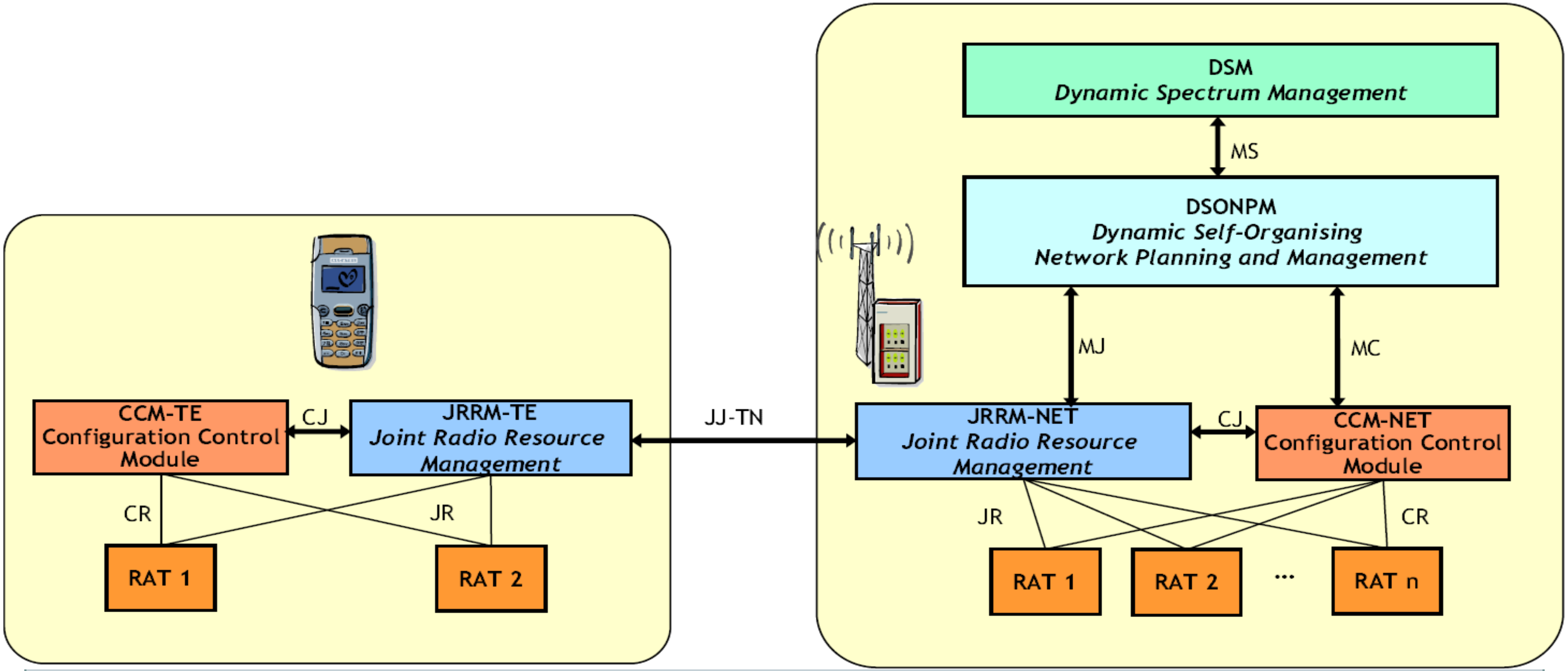
SDR Reference Architecture for Mobile Device



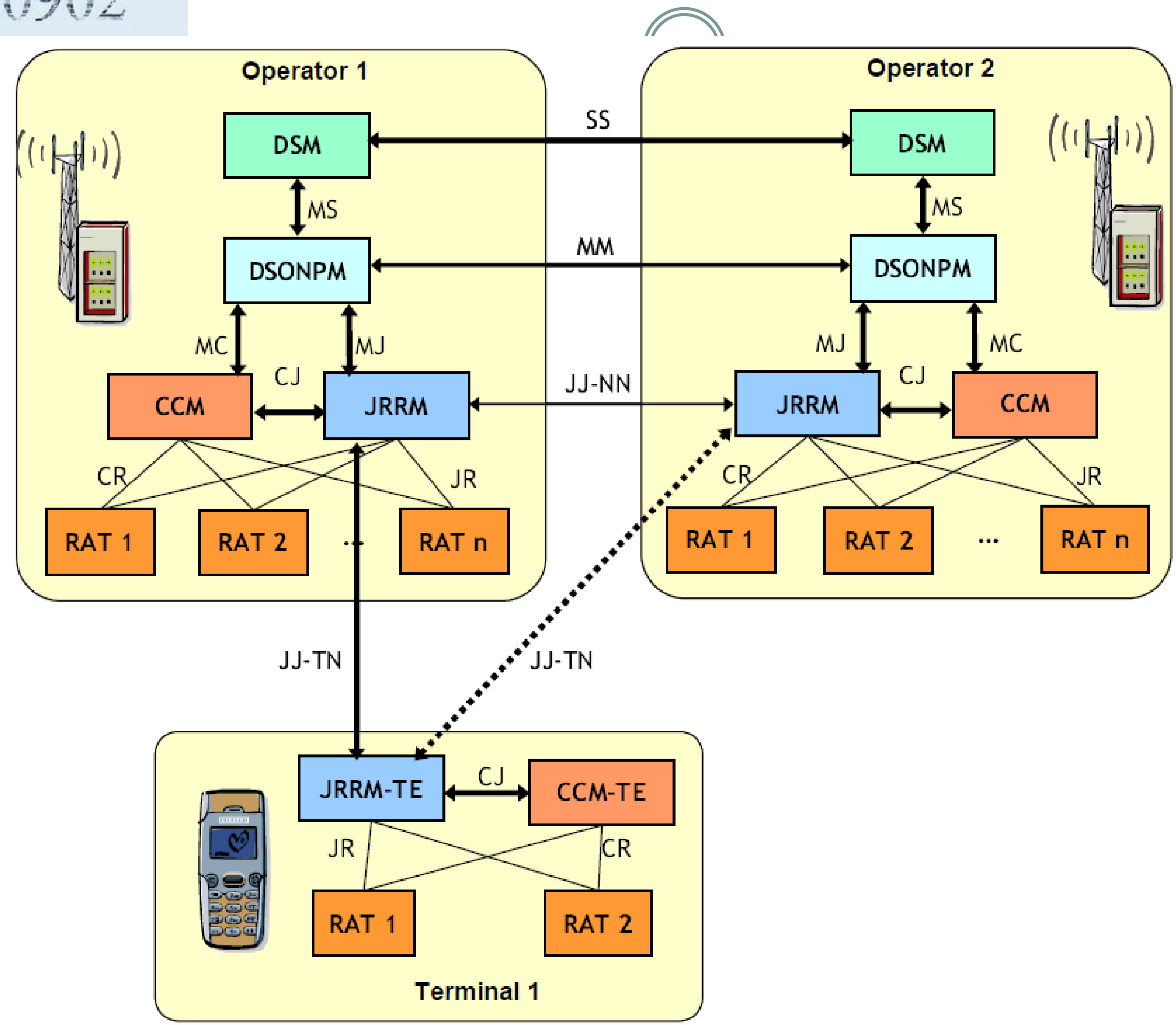
Radio Base Station (RBS)
Software Defined Radio (SDR)



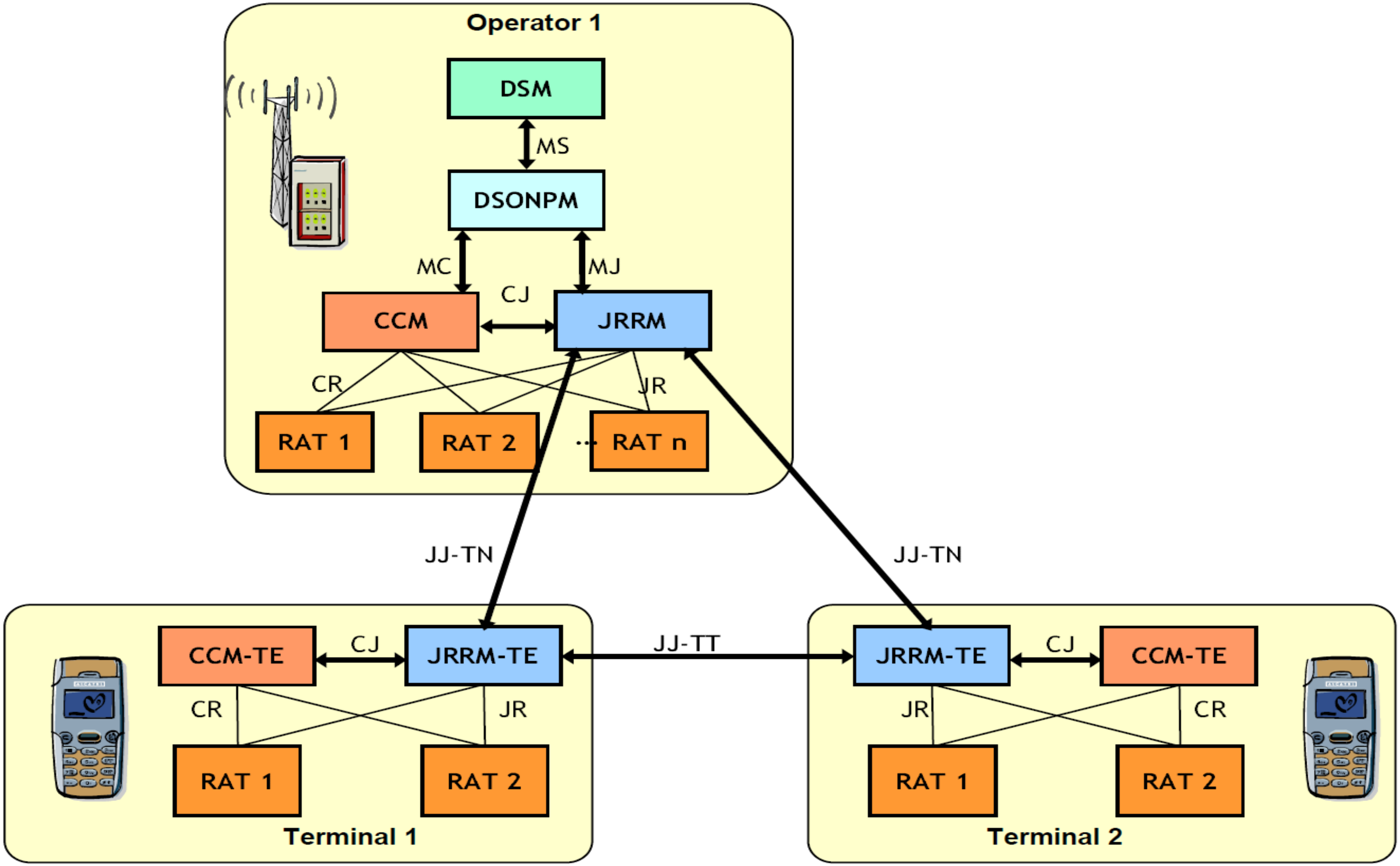
Functional Architecture (FA) for the Management and Control of RRS



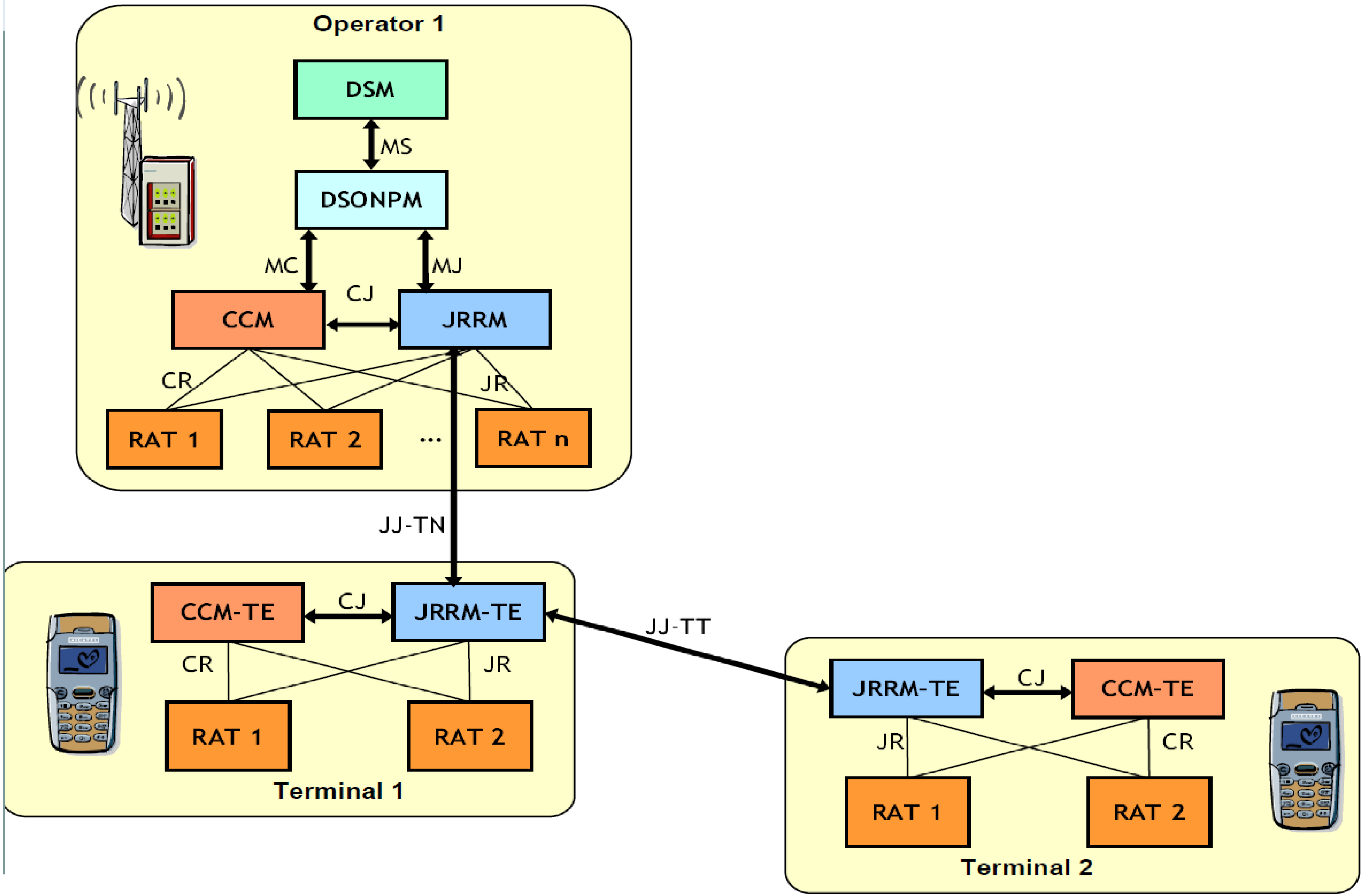
FA (multi-operator viewpoint)

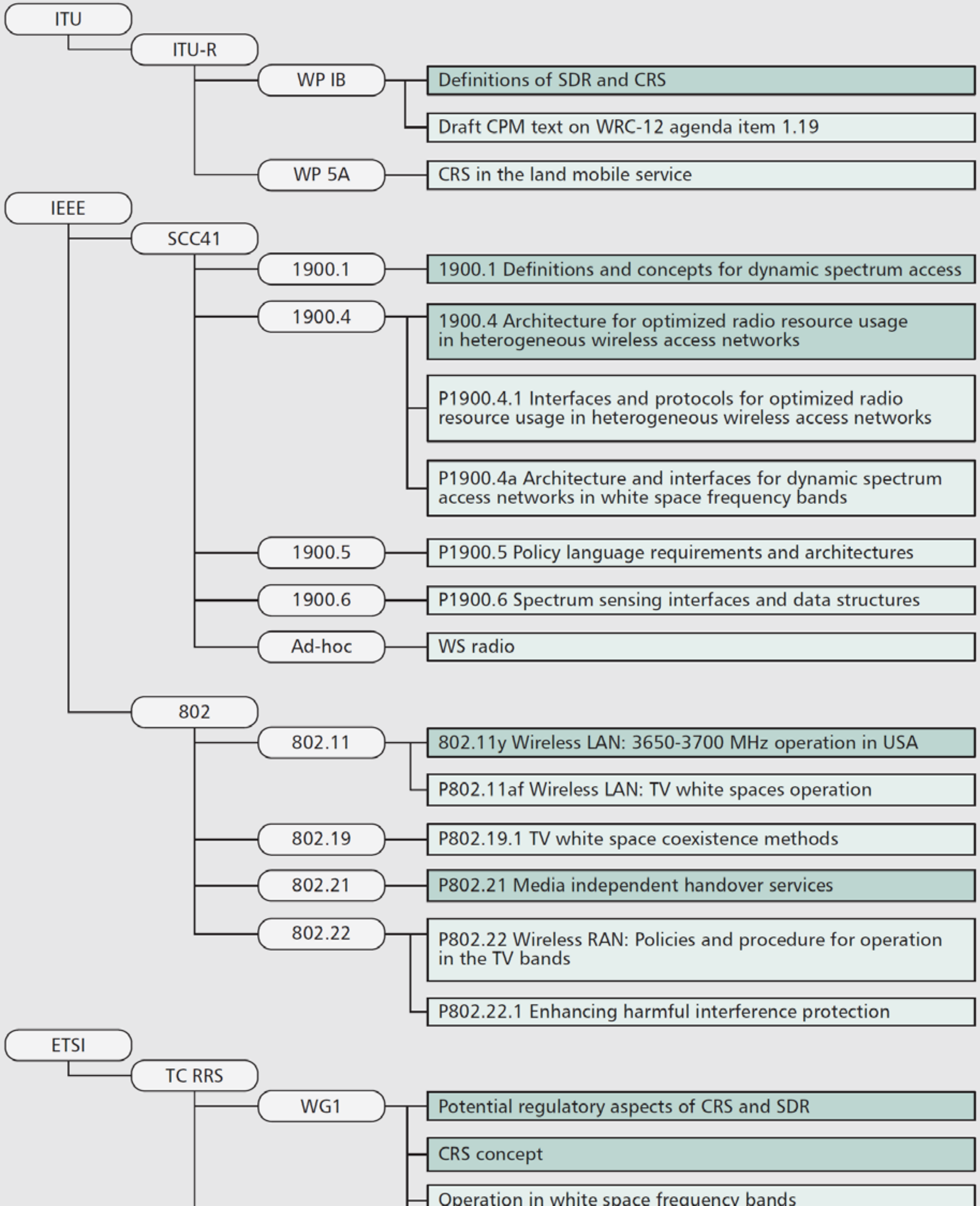


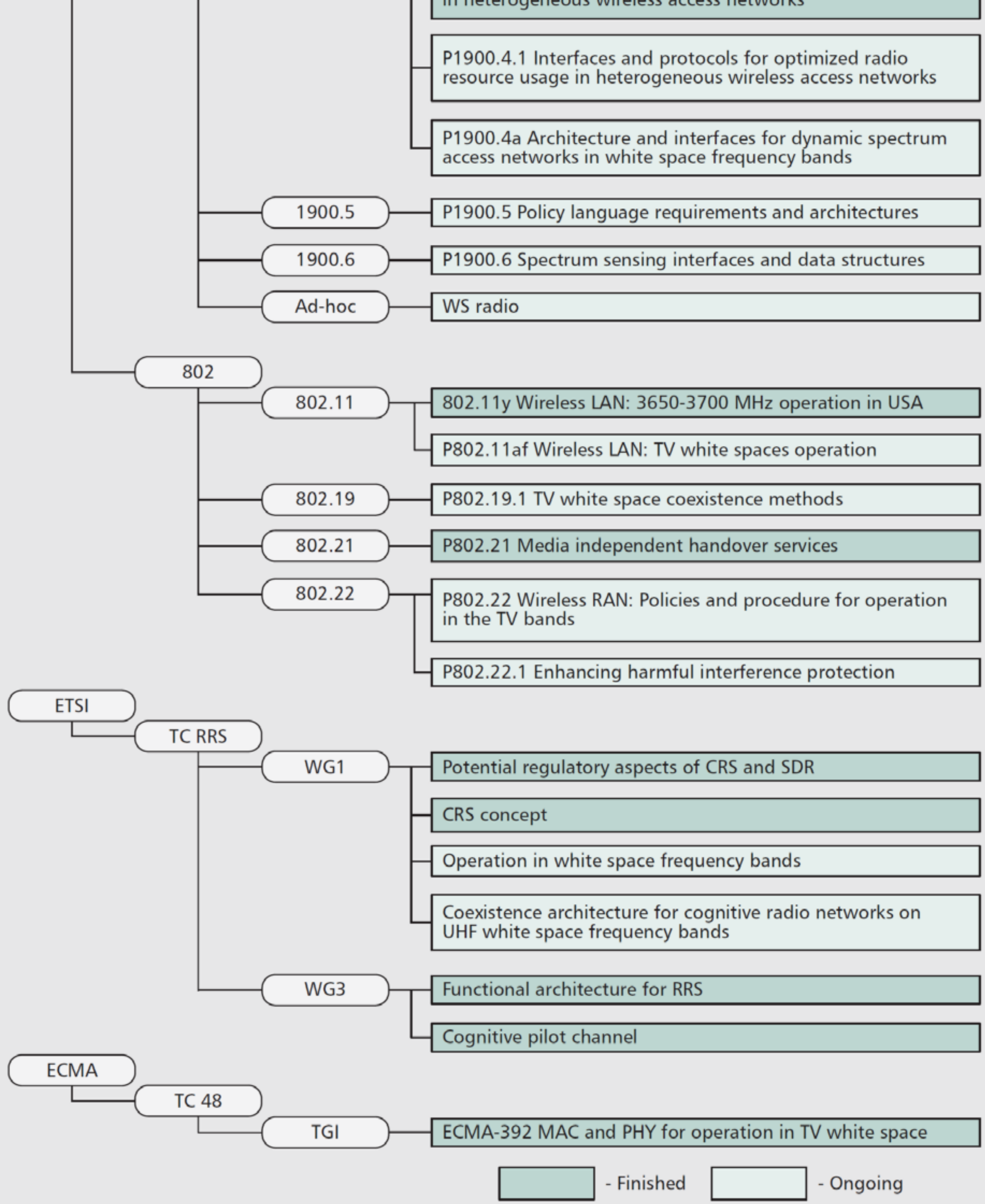
FA (Single-operator, multi-terminal viewpoint)



FA (multi-hop viewpoint)




ITU
ITU-R
WP IB
Definitions of SDR and CRS
Draft CPM text on WRC-12 agenda item 1.19
WP 5A
CRS in the land mobile service
IEEE
SCC41
1900.1
1900.1 Definitions and concepts for dynamic spectrum access
1900.4
1900.4 Architecture for optimized radio resource usage in heterogeneous wireless access networks
P1900.4.1 Interfaces and protocols for optimized radio resource usage in heterogeneous wireless access networks
P1900.4a Architecture and interfaces for dynamic spectrum access networks in white space frequency bands
1900.5
P1900.5 Policy language requirements and architectures
1900.6
P1900.6 Spectrum sensing interfaces and data structures
Ad-hoc
WS radio
802
802.11
802.11y Wireless LAN: 3650-3700 MHz operation in USA
P802.11af Wireless LAN: TV white spaces operation
802.19
P802.19.1 TV white space coexistence methods
802.21
P802.21 Media independent handover services
802.22
P802.22 Wireless RAN: Policies and procedure for operation in the TV bands
P802.22.1 Enhancing harmful interference protection
ETSI
TC RRS
WG1
Potential regulatory aspects of CRS and SDR
CRS concept
Operation in white space frequency bands


in heterogeneous wireless access networks
P1900.4.1 Interfaces and protocols for optimized radio resource usage in heterogeneous wireless access networks
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Potential regulatory aspects of CRS and SDR
CRS concept
Operation in white space frequency bands
Coexistence architecture for cognitive radio networks on UHF white space frequency bands
WG3
Functional architecture for RRS
Cognitive pilot channel
ECMA
TC 48
TGI
ECMA-392 MAC and PHY for operation in TV white space
- Finished
- Ongoing

back