“TIME ISN'T A STRAIGHT LINE. IT'S ALL... BUMPY-WUMPY. THERE'S LOADS OF BORING STUFF. LIKE SUNDAYS AND TUESDAYS AND THURSDAY AFTERNOONS. BUT NOW AND THEN THERE ARE SATURDAYS.”

- THE DOCTOR
OVERVIEW ON COGNITIVE RADIO CONCEPT AND APPLICATIONS

PHD COURSE "COGNITIVE RADIOS AND NETWORKS: THEORY AND PRACTICE"

LECTURER: ANDREA F. CATTONI
Agenda

• **Who??????????????**

• Overview on CR concept

• Main research fields and topics.

• History and visions: Mitola, Haykin.

• Application scenarios: terminal-centric reconfiguration, white spaces
Who the *^;?+)=# is this guy????

- MSc and PhD @University of Genova (‘04/’08)
- @AAU since 2008, now Associate Prof.
- Most common question asked: why did you leave those nice warm beaches for the cold DK?
- Second most asked question: why Berlusconi????
What is Cognitive Radio?

• **ITU**: A radio or system that senses, and is aware of, its operational environment and can dynamically and autonomously adjust its radio operating parameters accordingly.

• **FCC**: CR is a radio that can change its transmitter parameters based on interaction with the environment in which it operates.

• **NTIA**: A radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets.

• **WWRF**: Cognitive Radio employs a dynamic time-frequency-power based radio measurement and analysis of the RF environment, to make an optimum choice of carrier frequency and channel bandwidth to guide the transceiver in its end-to-end communication, with quality of service being an important design requirement.
What do they have in common?

• They talk about a "radio".
• They talk about interaction with the environment.
• They talk about measuring.
• They talk about decision making.
• They talk about autonomicity.
• They talk about adaptation.

Radio

Sense RF

Make Decision

Adjust

Environment
What do we get out of them?

- Without knowing anything beforehand, we can almost get the so-called "Cognitive Cycle".

- Do they really define what CR does, comes from and it is useful for?
  - **NO!**

- They are regulatory/framework definitions, used to set the stage for all the specific topics.

- More detailed definitions have been proposed along the way in literature.

- Before going deeper, let’s see a bit of history and the major players.
In the beginning was the Software Defined Radio…

RF Processing

A/DC

Modem

Network Stack

Why was it attractive?

Multi-standard Radio

Network Convergence

Std1  Std2  Std3

HW Resources

GPP/FPGA SW processing

HW Resources

Network Convergence

Std1  Std2  Std3

Why was it attractive?
Evolution path

• Multi-standard radio were considered the future in mobile terminals.
• Today we know it is true, but 20 years ago the first GSM phones were barely available.
• Today we incorporate:
  • 3G
  • GSM
  • WiFi
  • Bluetooth
  • GPS
• Cheap multi-standard via software re-configuration was a revolutionary concept.
Why was multi-standard reconfigurable radio useful?

- One of the main problem was the international compatibility
  - US had CDMA2000 and GSM in Europe
  - Even for the same system, e.g. GSM, there were different bands:
    - 900 MHz / 1800 MHz
    - 800 MHz / 1900 MHz
- The other application was emergency management / public service interoperability
  - Still today in US there are different radio systems for each county/city/force
- Military application is always present
  - International inter-force systems
One day someone decided to stitch a brain to it...

• The first appearance of the "Cognitive Radio" term was with J. Mitola.

• While developing XML for radio systems, he tried to join the artificial intelligence world with the radio one.

URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=788210&isnumber=17080
The big players (short bibliography)

- **Cognitive Networks**, Mahmoud.
- **Cognitive Radio Communications and Networks**, Wyglinski.
- **Cognitive Radio Technology**, Fette.
- **Cognitive Radio Architecture**, Mitola.
Why do we need CRN today?

Full convergence:
- Device (all-in-one)
- Network (full-IPv6)
- Service (cloud services)
The crunch
What the crunch is?

- Within 2020 Cisco foresees a x1000 wireless traffic increase.
- Spectrum allocated for broadband wireless will become too few already in 3 years time.
- While the charts show the licensed spectrum only, the same will hold for the "good" unlicensed also.
  - Good means that provides good coverage.
  - 60GHz is free but has "propagation issues".
- Nevertheless, in terms of usage, there is a trick!

http://money.cnn.com/2012/02/21/technology/spectrum_crunch/index.htm
http://www.fcc.gov/encyclopedia/spectrum-crunch
What the measurements say

- **Measurement Results:**
  - 30 MHz – 2.9 GHz
  - Max. utilization ~ 25%
  - Average usage ~ 5.2%
  - New York City average ~13.1%

- Spectrum is then statically allocated to a service, but it is not always in use.

The occupancy was defined as the fraction measured in time and frequency dimensions where the received signal strength exceeds a threshold.

Spectrum holes

• After the FCC studies from ’02 [1] it was clear that there were opportunities for better spectrum utilization.

• This opportunities were called spectrum holes and they are defined as a point in frequency, time, and space which is not occupied by any transmission and it can be used by a ”secondary system” without interfering with a ”primary one” [2].

• Ten years passed, are we ready for this type of exploitation?
  • NO!
  • Technology limitations (RF bandiwdth, A/DC conversion band)
  • Regulatory process speed and requirements

Pandora’s vase was opened

• The definition of CR came out in 1999/2000.
• The FCC reports are from 2002.
• Since then research activities were flourishing floating around the CR world.
• Among them we can mention:
  • Spectrum Sensing
  • Spectrum Management
  • Radio Resource Management
  • Air Interface definition
  • Hardware (HW) and Software (SW) platform development
Setting the vocabulary (1)

- In all the research activities, the progresses have been made in multiple scientific fields from both the theoretical and the practical perspectives.

- **Spectrum Sensing**: algorithms and techniques for understanding what is in the air.

- **Spectrum Management**: making active decisions on how to optimally use the available spectrum.

- **Radio Resource Management**: making active decisions on how to optimally use the available local resources for guaranteeing the best user/application experience.
Setting the vocabulary (2)

- **Air Interface definition**: development of new transmission methodologies for improving current systems (e.g. OFDMA) or going beyond them for improving the spectral efficiency.

- **HW development**: developing new devices and tools that enable the real usage of the massive amount of algorithm.

- **SW development**: developing new software radio platform for enabling real CR experimentation.
In practice, how CR should be?

• Along time, several CR visions have been proposed in literature.
• Each one was targeting the specific needs of the proposer.
• All of them are based on derivation of the so-called *cognitive cycle*.
• Let us analyze two of them:
  - Mitola’s (2000)
  - Haykin’s (2005)

Which are the characteristics of Mitola’s CR

Characteristics:
• Multi-standard: able to exploit different communication technologies.
• Terminal centric: the PDA itself is the CR.
• User-oriented: aware not only of the radio environment but also of the user one; able to detect events in different domains.
• Advanced features (voice recognition, video processing etc.)

Main goals:
• Opportunistic usage of the available STANDARD networks (maybe with a tiny bit of network intelligence)
• Improvement of user’s Quality of Experience (QoE).
Mitola’s Cognitive Cycle

• It reflects the basic characteristics of a CC.
• It is not specifically related to the RF/radio environment.
• It is an artificial intelligence-driven diagram.
Haykin’s vision

• Haykin’s vision is more practic.
• Closer to the radio world.
• Oriented to signal processing and to technology in general.
• It provides specific terminal features.
• The paper provides a good algorithmic overview, also at "network-side"

Main goal:
• Opportunistic usage of the spectrum
Haykin’s CC

The main characteristics of a PHY for CR defined by Haykin in ’05:

- Spectral Analysis
  - Channel Availability (Spectrum Holes)
  - Interference Analysis
- Channel quality/state estimation (CSI)
- Available capacity analysis
  - Rate feedback
- Dynamic Spectrum Allocation
- Traffic Analysis
- Adaptive Signal TX/RX
  - Power Control
  - OFDM
  - MIMO
  - Turbo Processing
Mitola’s scenario: user/terminal centric

Reconfigure system and band according to the country

Baker Street 221b, please!

Connect to the cell

All the cells along the road are pre-alerted of potential handover

Speech recognition detects the destination address
Cognitive WRAN based on TV White Spaces

• Several TV channels used by local/regional broadcasters are often temporarily vacant

• Given the long-range coverage:
  • Cheap spectrum solution (unlicensed / lightly licensed).
  • Provision of broadband in difficulty accessible areas.
  • Avoid expensive cable deployments to operators.

• Main intention was to exploit opportunistic, sensing-based access

QOSMOS EU FP7 Project webpage
IEEE 802.22: the first Cognitive WRAN standard

- Especially in US there was a great interest in such scenario, given the huge amount of rural areas.

- IEEE decided to ride the wave and the IEEE 802.22 was born.

- In only 3/4 years they came out with a draft standard for such application.

- It was "inspired" in some main characteristics by the more mature 802 standards:
  - 802.11 (WLAN, aka the commercially known WiFi)
  - 802.16 (WMAN, aka WiMAX)
Comparison with IEEE standards

URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4752688&isnumber=4752663
The superframe structure addresses the processes with slow dynamics (e.g. spectrum allocation).

Fast frames for low latency data transmission

Header-based scheduling info

Fixed allocation for "access channel"

Beacon-based inter-cell coexistence signalling

The superframe structure addresses the processes with slow dynamics (e.g. spectrum allocation).
Modern scenarios

• FCC database-based access
  • Brief overview on the concept
  • Network architecture
  • Terminal product
  • Running trial
• Extension of the concept: Authorized Shared Access
  • Regulatory/contract concept
  • Technical foreseen architecture
  • Potential usage
Today’s TVWS

- After a long discussion, FCC removed spectrum sensing from the TVWS requirements.
- The new solution is based on geolocation databases.
- Several companies are nowadays “on trial” for getting the license of DB operators (MS, Google).
- The first trial deployments are ongoing, mainly driven by Spectrum Bridge, using the KTS radio.

FCC Database Administration Guide
http://www.fcc.gov/encyclopedia/white-space-database-administrators-guide
TVWS Database-based Access

Spectrum Bridge LLC
http://www.spectrumbridge.com/ProductsServices/WhiteSpacesSolutions/Overview.aspx

Google WS DB Proposal

A N D R E A  F. C A T T O N I
PHD COURSE “CRS AND CNS: THEORY AND PRACTICE”, TCD, DUBLIN

13-16 May 2013
Generalization of the concept: Authorized Shared Access

- In order to extend and generalize the DB-based access is now pushed by some companies a concept called Authorized Shared Access.

- Main differences with WS
  - This is a licensed framework
  - It is not targeting the access of single UE devices but cells.
  - The regulator has a direct role in certifying the licensees.
  - The "lease" of the spectrum happens through a direct agreement between the spectrum owner and the specific ASA-licensee.
  - It should provide Quality of Service (QoS) to the licensee.
Authorized Shared Access architecture

• ASA is a regulatory framework, not a technical solution.
• Nevertheless it has strong technical impact.
• 3GPP already started thinking about an inclusion in LTE-A.

CEPT CG CRS (12)04
The practical path towards CR

• In the beginning all the smartness was supposed to be in the UE.
  • ... and no, smartphones are not smart enough!

• Along the years the intelligence has been moved also into the network.

• The network, as a matter of fact, can deal/exchange/process more information and then being considered as part of the distributed intelligence.

• Already today we have some examples of smart systems.

• Let’s take for example the buzzed LTE/LTE-A
Mapping between CR requirements and LTE-A capabilities

**Haykin’s CR in ’05:**
- Spectral Analysis
  - Channel Availability (Spectrum Holes)
  - Interference Analysis
- Channel quality/state estimation (CSI)
- Available capacity analysis
- Rate feedback
- Dynamic Spectrum Allocation
- Traffic Analysis
- Adaptive Signal TX/RX
- Power Control
- OFDM
- MIMO
- Turbo Processing

**LTE-Advanced features:**
- Multi network sensing
  - Carrier sensing
  - RSRP of other cells/networks
- CSI/CQI (also with compression)
- Capacity estimation for scheduling
  - AMC/link adaptation
  - AOCS/carrier aggregation
  - QoS and scheduling
- Flexible air interface
  - FPC (and DTX/DRX)
  - OFDMA – SC-FDMA
- Several MIMO modalities (including CoMP and MU-)
  - Turbo encoding/decoding
Self Organizing Network features (SON)

- **Traffic steering:** Offloading solutions and distribution of the traffic over all the layers (from macro to femto).
- **Multi-RAT:** Integration of multiple TX technologies (2G-3G) and inter-RAT handover for better coverage/balancing.
- **Automatic Neighbor Relation function:** Build and maintains neighbor relations though sensing and reporting performed by the active UEs.
- **Automatic Cell ID (PCI) selection:** Based on UE sensing and local cooperation with neighbor eNBs.
- **Dynamic configuration of X2 and S1 interfaces:** Autonomous configuration of the control plane backhaul with gateway and neighbors.
- **RACH parameters optimization:** Local information exchange about the usage of the Random Access Channel for interference avoidance.
- **Mobility parameters optimization:** Self-adaptation of the mobility parameters for increasing robustness and load balancing.

LTE-Advanced foresees automatic network configuration and self-optimization of several parameters all along the protocol stack layers.
But how will it be in the future?

- **System evolution**: we take the current systems ad we go on improving them and squeezing as much as possible, especially in terms of capacity.
  - LTE-A – improved SON, spectrum flexibility and carrier aggregation...
  - 802.11ac – dynamic bandwidth aggregation, dynamic channel selection...

- **System revolution**: we design a completely new system, dropping the cumbersome backward compatibility. But usually a system revolution is based on a PHY revolution. So, what’s after OFDMA?

- **Cloud RAN**: everything become a cloud. Spectrum, baseband, RF, everything is in a unique pool that is used when/where/how needed.
How to discuss with me on CR/5G

- Blog: blog.asgard.lab.es.aau.dk
- Follow us! (Twitter): @asgard_aau
- YouTube channel: www.youtube.com/user/AsgardAAU
- My email: afc@es.aau.dk
Overview on Cognitive Radio

• **What** is CR?
• **When**: where does it come from?
  • SDR
  • Reconfigurable radios
  • Multi-standard
• **Who**?
  • Mitola, Fette, Haykin, Jondral, Reed, Bostian
• **Why**?
  • Spectrum overcrowdness
  • One device for everything
  • Spectrum holes
Main Research Fields and Topics

- Main research topics:
  - Spectrum sensing
  - Spectrum allocation
  - Radio Environment maps
  - Air interface design
  - Testbed development
History and Visions

• Mitola
  • Multi-standard terminal
  • User-oriented (user environment awareness)
  • Opportunistic usage of the available **STANDARD** networks
  • advanced features (voice recognition, video processing etc.)

• Haykin
  • Comms oriented
  • Specific terminal features
  • Opportunistic usage of the spectrum
  • LTE-like
Traditional scenarios

- Mitola: user centric reconfiguration
- TV white spaces: the potential
- IEEE 802.22
  - Origins
  - Evolution from WiMAX
  - The frame format
  - The "contention-based access part"
On the practical path

• The Cognitive Radio Network concept
  • Terminal AND network are smart
  • Moving the intelligence in the network/access point
• Today’s application: LTE
  • Mapping with Haykin’s vision
  • SON
• Tomorrow’s application
  • B4G concepts
  • Evolution vs revolution