

Cognitive Radio Communication and Networking

AN OVERVIEW-PART I

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Outline

- Introduction
- Motivation
- Spectrum Sensing Techniques
- Spectrum Access and Sharing
- Agile Transmission Techniques
- Propagation issues for cognitive radio
- Reconfiguration, Adaptation and Optimization

INTRODUCTION

- Cognitive radio is a radio that is aware of its surrounding environment.
- Extension of software defined radio (SDR).
- It has intelligent adaptation of environmental changes by self-reconfiguration of its parameters.
- Enhancement of real-time experience of the end user and increase the spectrum utilization.
- Several functionalities: Spectrum sensing, Dynamic spectrum access, interference management and optimization of the usage of radio resources.
- Interoperable with existing technologies.
- Respect the spectrum regulations.

MOTIVATION

- The spectrum is about to reach a crisis (no more available BW to sell).
- Evolution of wireless technologies increases the demand on spectrum and QoS.
- Licensed spectrum is underutilized (proved by FCC on 0-6 GHz band).
- Spectrum holes exist and their exploitation increase the quality of the user experience.
- CR is the proposed solution for using the holes without harming the existing systems.



Professor Joseph Mitola, III
(SENIOR MEMBER, IEEE)

- Introduces the concept of CR in 1998 at Royal Institute of Technology-Stockholm.
- Published in 1999.

SPECTRUM SENSING

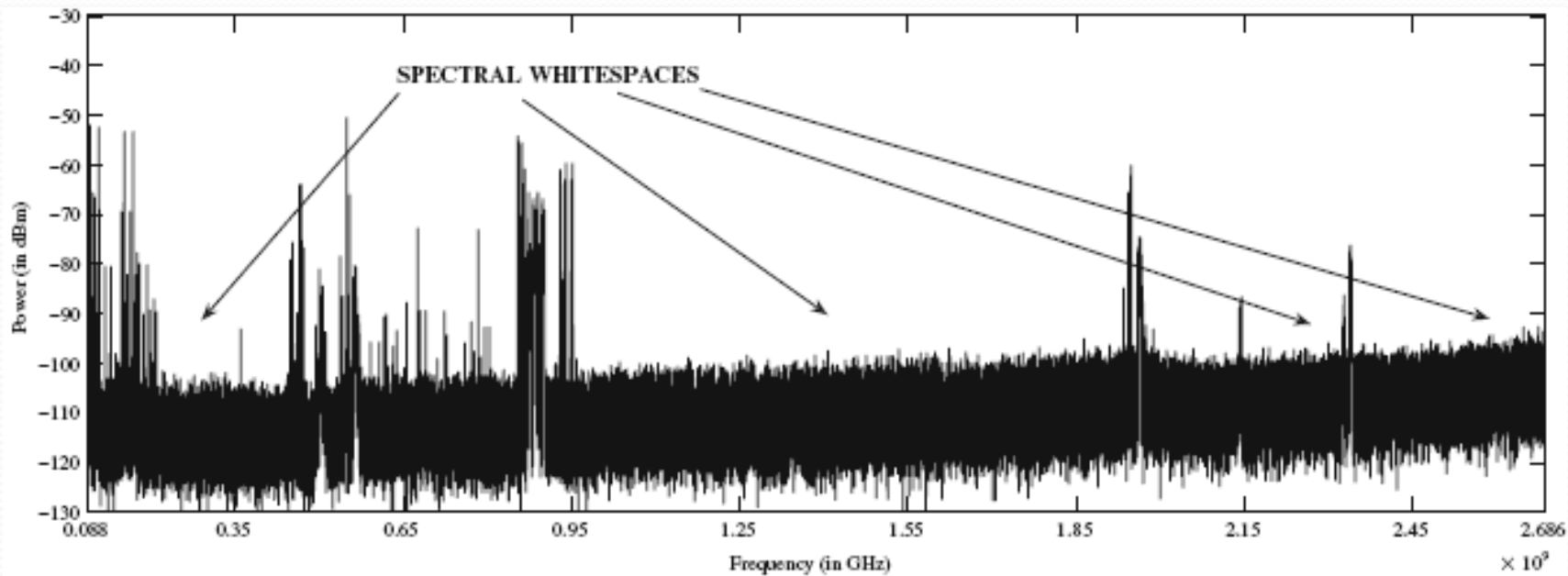


Fig. ref [1]: power spectral density (PSD) measured on July 11,2008 in Worcester, Massachusetts.

- Essential functionality of CR device..
- Secondary users need to detect primary user (PU) signals and white spaces(spectrum holes).
- First step toward spectrum opportunity to gain access.

SPECTRUM SENSING

Detectors

Detectors:

- Energy Detector(ED): blind detector.
- Cyclo-stationary detector: exploit the property of modulated signals.
- Matched filter detector(pilot-based): if PU signal is known to CR user.
- Eigen value based detection: multiple-antenna receiver and unknown signal.
- Cooperative Spectrum Sensing.

SPECTRUM SENSING

Energy detector(ED)

- Distinguishing between signals from their energy levels.
- Uses binary Hypotheses: H_0 under noise and H_1 if the PU signal exist.
- Then, performs log-likelihood ratio: $LLR = \log\left\{\frac{p(Y/H_1)}{p(Y/H_0)}\right\} \leq \text{or} \geq \text{threshold}$
- It has low complexity.
- Fails at **low SNR**.
- Correct states: $P\{\text{Detection}\}$ and $P\{\text{Noise}/H_0\}$.
- Errors: False Alarm(FA) and Missed Detection(MD) probabilities.

SPECTRUM SENSING

Cyclo-stationary detector

- Modulated signals are usually periodic and stationary processes, where noise is not.
- It tests the correlation of the received signal over different periods in time to distinguish between primary signal and noise.
- Has higher complexity than **ED**, but can work in very-low **SNR** regions.
- Suggested by FCC to enhance detection capability of CR device.

SPECTRUM SENSING

Matched Filter (MF) detector

- Most of primary systems has pilots, preambles, and training sequences.
- Optimal in AWGN channel and has coherent detection (phase locking to the carrier wave).
- At low SNR, it has large estimation error.
- Complexity: different types of primary signals to monitor in wide band.
- Performance degradation: if timing between CR and PU is not perfectly known, then exhaustive search for time offset is needed in order to lock at its specific phase.

SPECTRUM SENSING

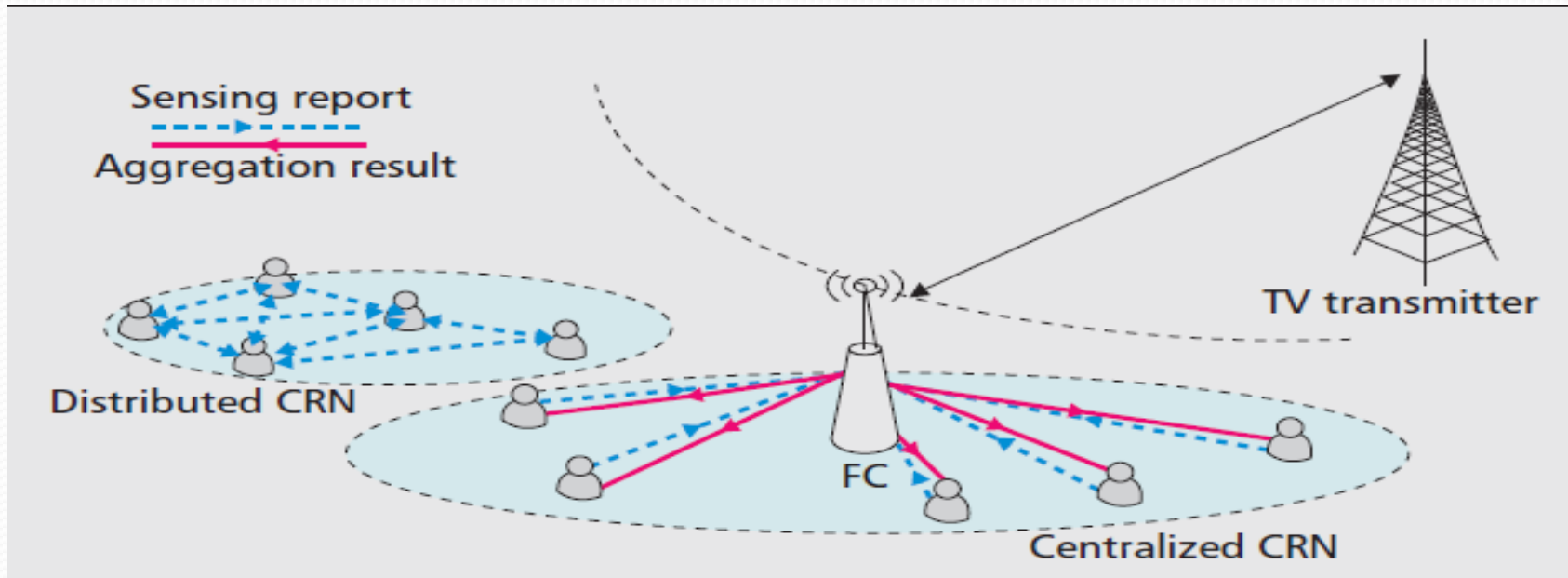
Eigen value based detector

- If the CR receiver is occupied with **multiple antennas**.
- The detector estimate the noise variance and signal power on different antennas to construct the covariance matrix.
- From the covariance matrix, the ratio between max. and min. Eigen values is computed.
- If the ratio equals to **one**, then no primary signal and vice versa.

SPECTRUM SENSING

Cooperative spectrum sensing

- Single detector performance is not sufficient → cooperative sensing.
- Two fashions: **centralized** and **decentralized**.
- In centralized:
 - Nodes report sensing values to a Fusion Center(FC).
 - Fusion rule: Soft or Hard in order to take the decision.
- In decentralized:
 - Ex.: Amplify and Forward(AF) between each other.



SPECTRUM SENSING

Cooperative spectrum sensing-Centralized CRN, Soft combination

- K users each takes N samples and sends them to a fusion center.
- Requires significant bandwidth for all reports of users.

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

- $\alpha = K/N$, σ^2 is the noise variance.
- λ_i 's are the Eigen values of $(1/N)YY^H$
- Two hypotheses at the FC.
- $y_k(n)$: sample by k^{th} user at n^{th} time instant.

SPECTRUM SENSING

Cooperative spectrum sensing-Centralized CRN, Soft combination

- If the σ^2 is **known** to FC, then H_0 as a decision if:

$$\lambda_i \in [\sigma^2(1 - \sqrt{\alpha})^2, \sigma^2(1 + \sqrt{\alpha})^2]$$

- If the σ^2 is **unknown** to FC, then H_0 as a decision if:

$$\frac{\max_i \lambda_i}{\min_i \lambda_i} \leq \frac{(1 + \sqrt{\alpha})^2}{(1 - \sqrt{\alpha})^2}$$

- Otherwise, H_1 is taken as a decision means the existence of a primary signal.

SPECTRUM SENSING

Cooperative spectrum sensing-Centralized CRN, **Hard combination**

- Nodes send quantized reports to FC.
- Reports are 1-bit or 2-bit indicating the energy region seen at the sensor.
- The Fusion Rule can be(in 1-bit reports case):
 - majority rule: K out of N votes.
 - OR rule: **one** out of N votes.
- For 2-bits report: ex. fuzzy logic can be applied.

SPECTRUM SENSING

Cooperative spectrum sensing Decentralized CRN

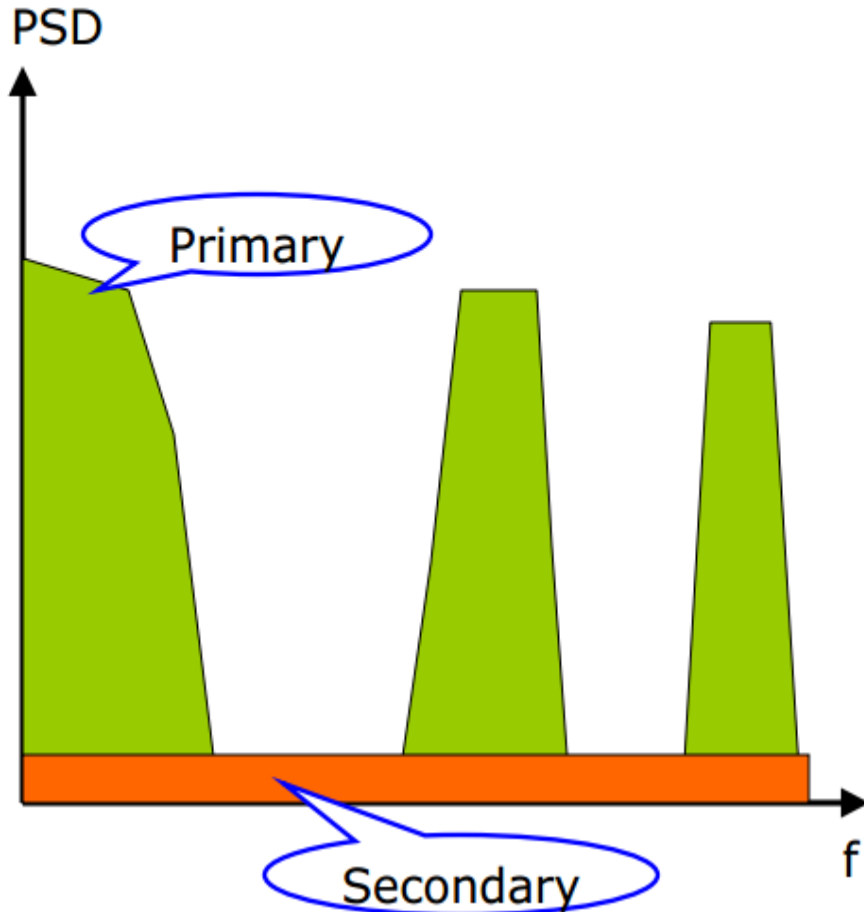
- Amplify and Forward used.
- Cognitive nodes share info. through local communication.
- The middle relay node forward from source to sink.
- Time slots needed (for transmission and relaying).
- Continuous sensing: during relay the source listen to the spectrum.
- needs algorithms for management for who speaks first to avoid collision between nodes.

SPECTRUM ACCESS AND SHARING

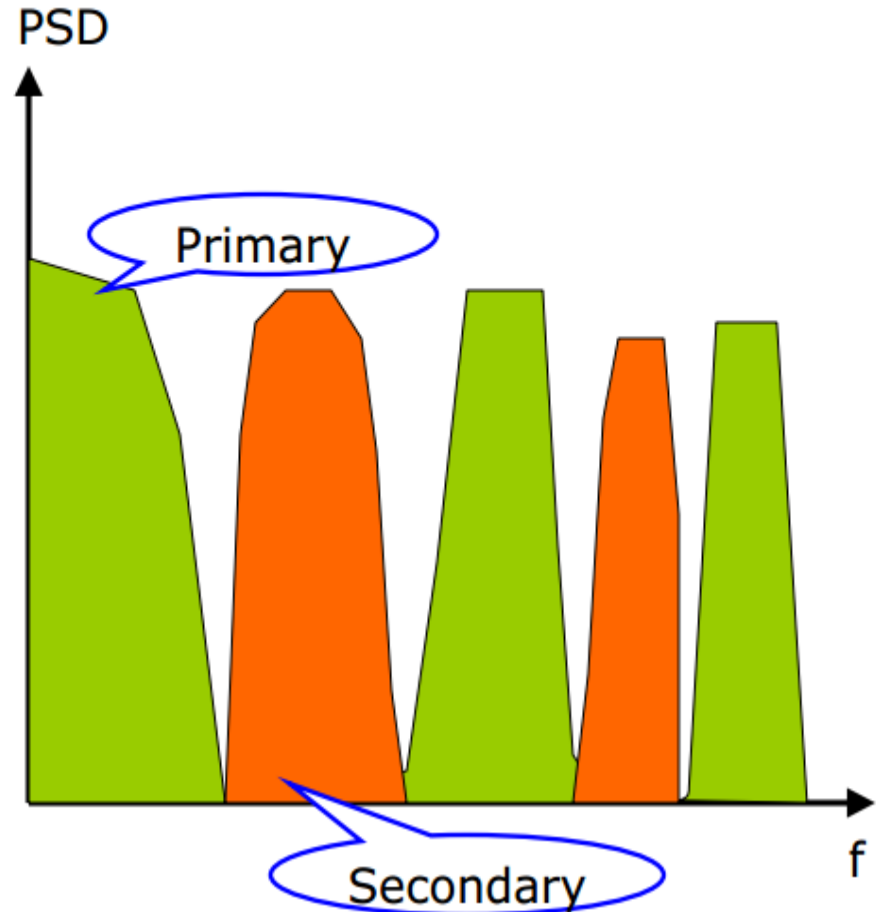
- Secondary Spectrum Access (SSA): access of cognitive devices to PU spectrum.
- Two Paradigm:
 - Non real-time: PUN is not active in certain time and space.
 - interference avoidance (spectrum interweave).
 - requires an agreement.
 - Real-time: Both PU and SU exist at the same time.
 - negotiated and opportunistic.
 - access techniques:
 - interference controlling (spectrum underlay).
 - interference mitigating (spectrum overlay).

SPECTRUM ACCESS AND SHARING

Spectrum Underlay (UWB)



Spectrum Overlay (OSA)



SPECTRUM ACCESS AND SHARING

- Interweave(non-real time):

- SU accesses the band where PU signals doesn't exist (space and time), a pre-agreement.

- Using orthogonal transmission like TDMA or FDMA for interference avoidance.

Real-time

- Negotiated:

- SU and PU should be able to connect via cognitive pilot channel.

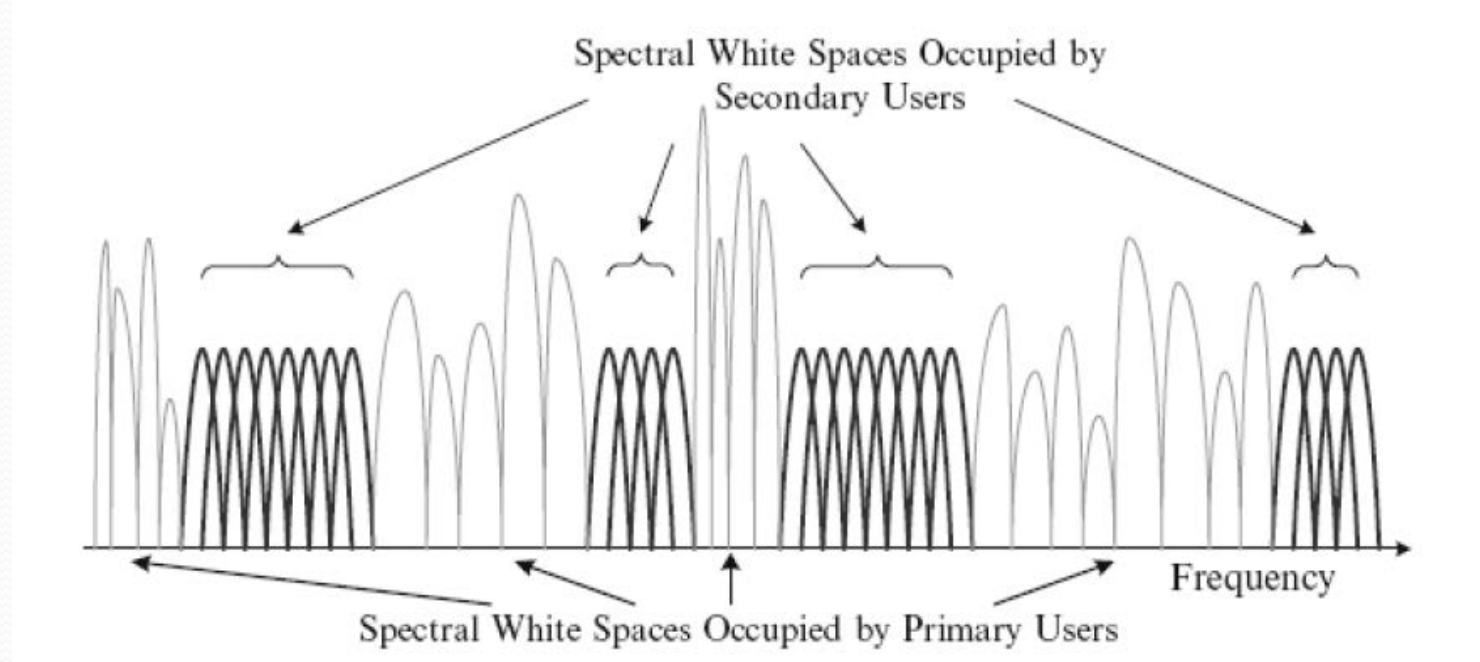
- PU informs SU about the opportunity in the pilot (explicit and implicit)

- Opportunistic:

- No medium between SU and PU.

AGILE TRANSMISSION TECHNIQUES

- Agility to increase CR rate and **avoid interference** on PU.
- Spectrum pooling (collect holes from different operators):



- Candidates: **NC-OFDM, NC-MC-CDMA.**

AGILE TRANSMISSION TECHNIQUES

OFDM-issues

Issues in OFDM:

- **Spectrum shaping** (to avoid interference on the adjacent channels).
- **PAPR**: Peak to average power ratio (distortion to carriers in vicinity).
- **Efficient radio implementation** (need for fast computation in hardware).

AGILE TRANSMISSION TECHNIQUES

OFDM-Spectrum shaping

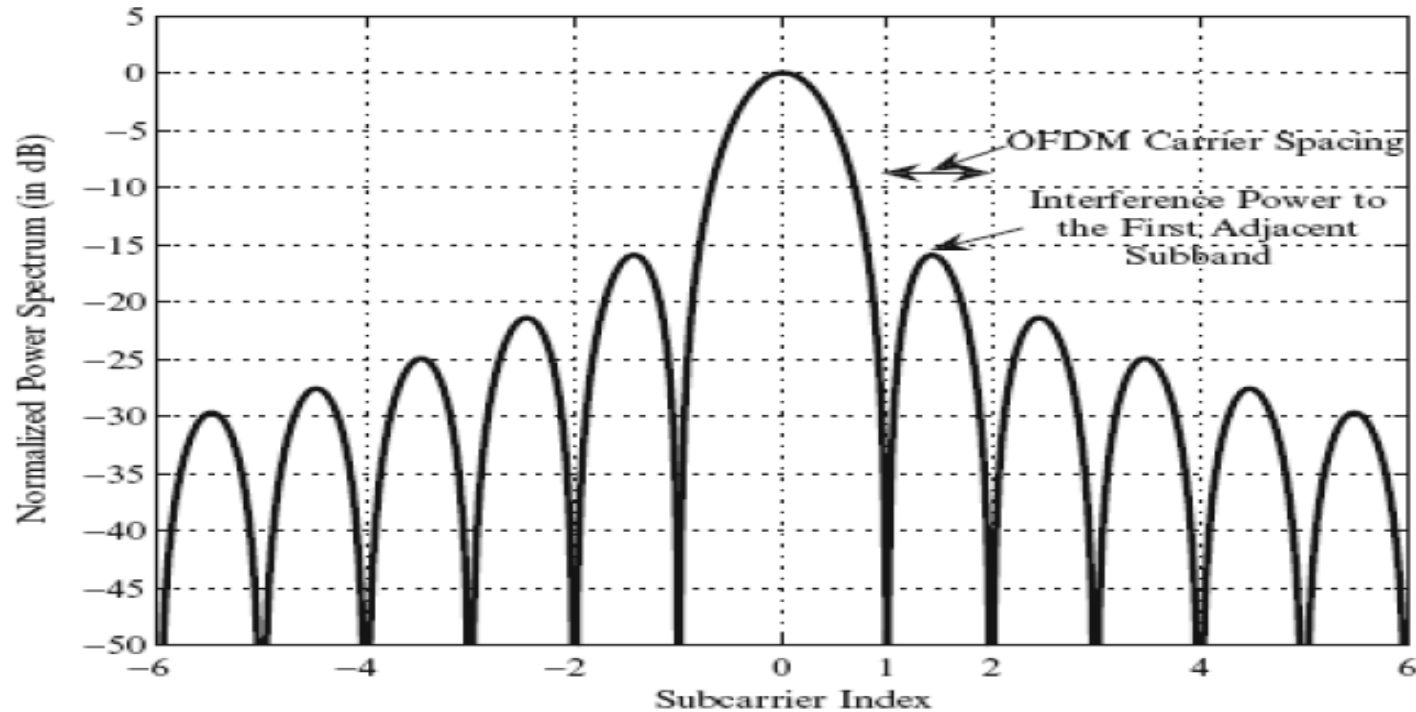


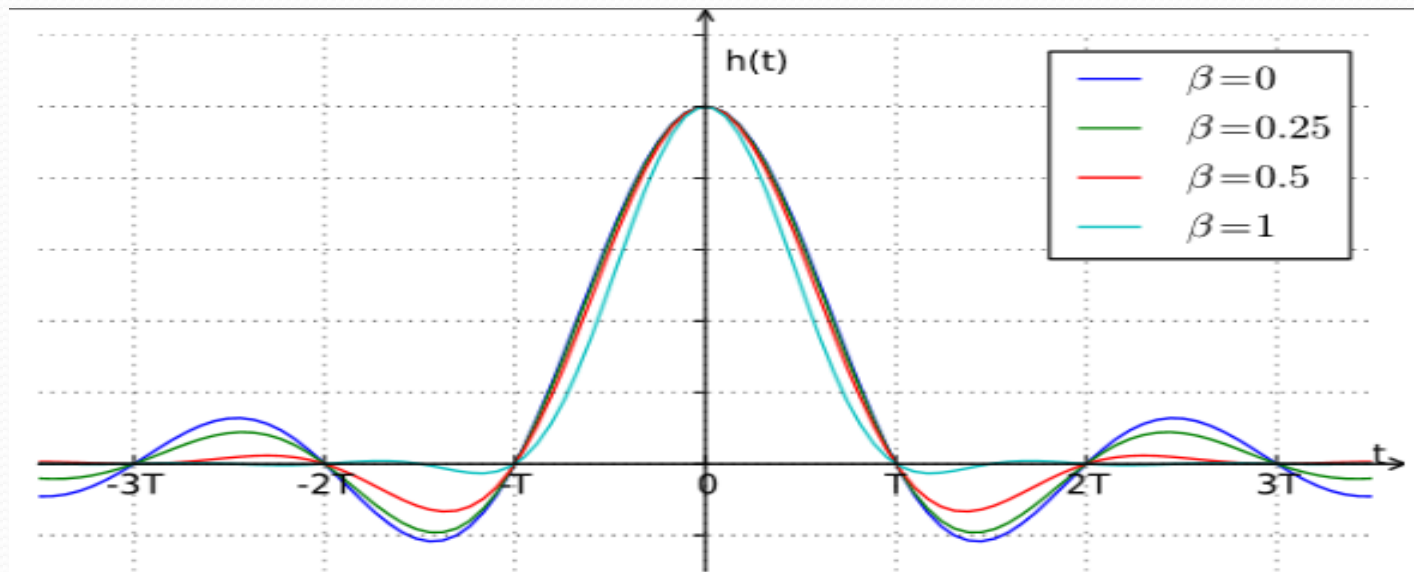
Figure: PSD of OFDM-modulated carrier, shows sub-carrier spacing and interference power to the side lobes of adjacent band (between real and considered sub-band).

Solutions: **windowing**, **subcarrier deactivation**, **cancellation of subcarriers**... many others

AGILE TRANSMISSION TECHNIQUES

OFDM-Spectrum shaping solutions, **Windowing**

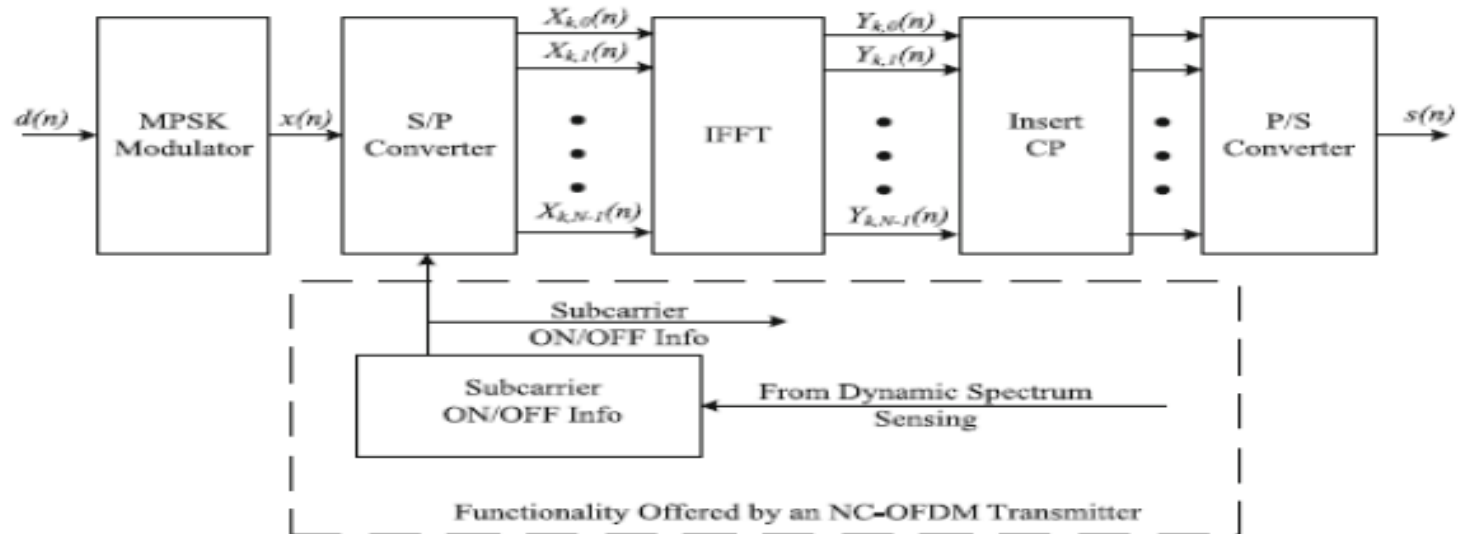
- Filter OFDM symbol in time domain with **raised cosine filter** for pulse shaping.



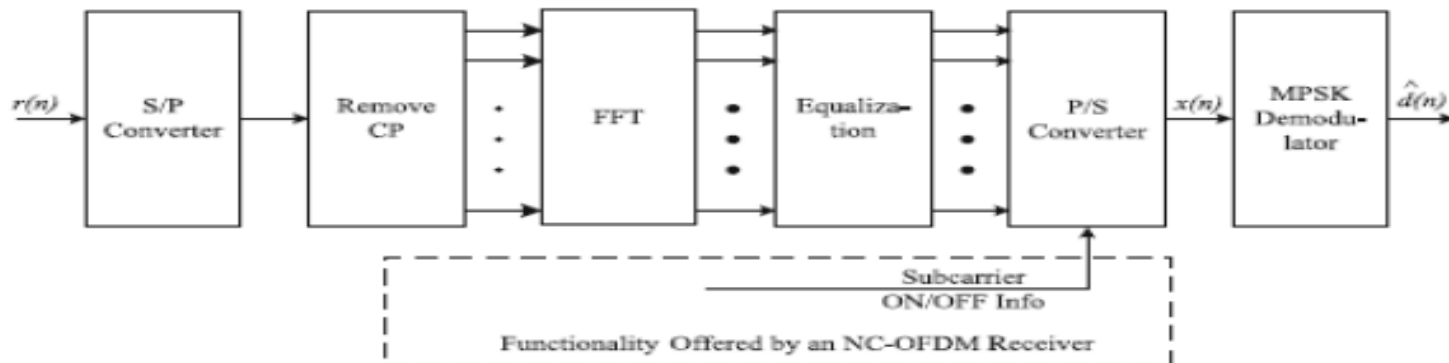
- Advantage: reduce side-lobes effect.
- Disadvantage: increase symbol duration by $(1+\beta) \Rightarrow$ decreases the throughput.

AGILE TRANSMISSION TECHNIQUES

OFDM-Spectrum shaping solutions, Subcarrier deactivation



(a) NC-OFDM Transmitter.

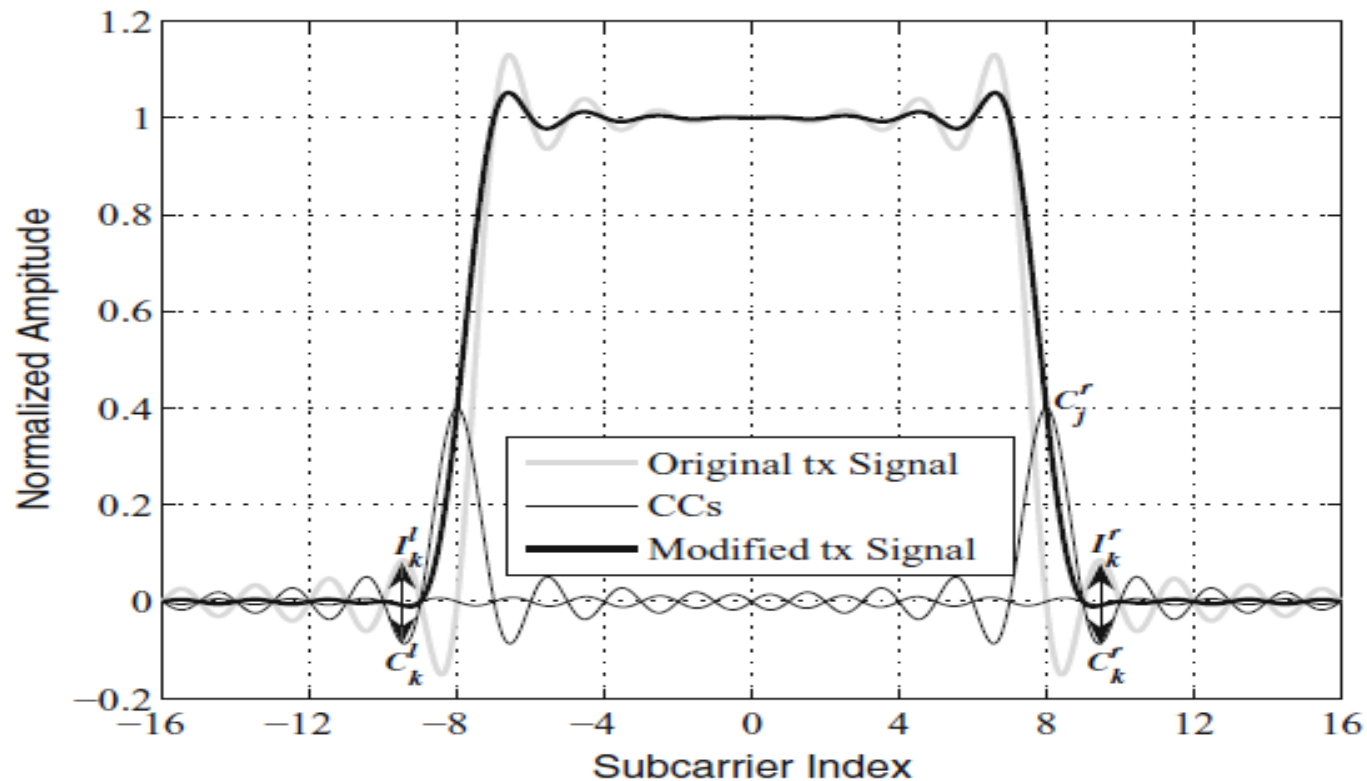


(b) NC-OFDM Receiver.

AGILE TRANSMISSION TECHNIQUES

OFDM-Spectrum shaping solutions, Cancellation of subcarriers

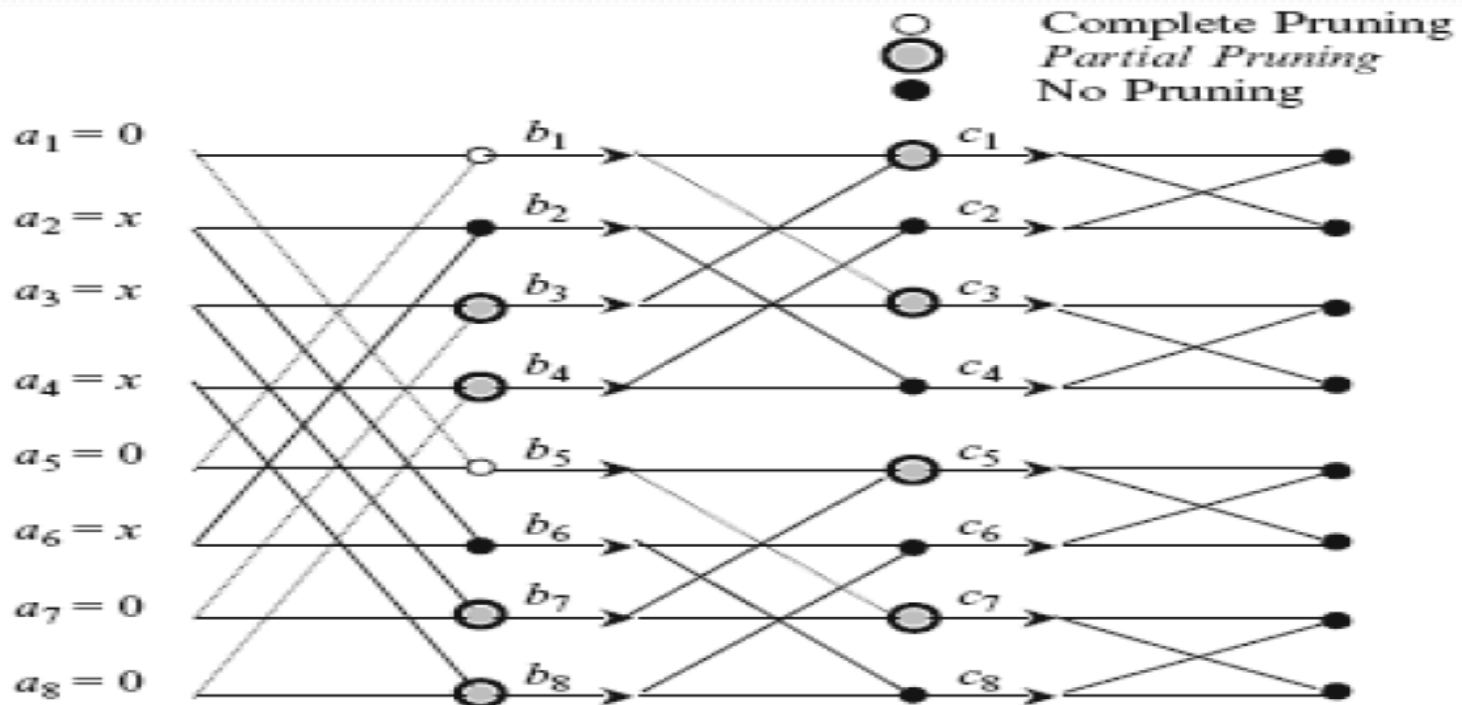
- Insertion of sub-carrier with same amplitude but opposite sign of side lobe.



AGILE TRANSMISSION TECHNIQUES

OFDM-Efficient implementation solution, FFT pruning

- Off-subcarriers have zero value at FFT and IFFT.
- Don't compute them again → **faster**.
- Convenient for devices with limited hardware capability.



AGILE TRANSMISSION TECHNIQUES

OFDM-PAPR

- It is the ratio between maximum instantaneous power and average power of OFDM symbol:

$$PAPR(s(t)) = \frac{\max_{0 \leq t \leq T} |s(t)|^2}{E\{|s(t)|^2\}}$$

- It causes high distortion to carriers in vicinity.
- Highly correlated signals lead to high PAPR.
- Solution:
 - Total power adjustment: if the sub-carrier is off, **divide** its power on active sub-carriers.

PROPAGATION ISSUES FOR CRN

- Licensee can control transmitted power but channel controls the power seen at receiver.
- Bands less than 3.5 GHz have less propagation loss → good candidates for CR.
- Effects: fading, multipath, shadowing, scattering, etc...
- **Large-scale** fading sensitive to carrier frequency and **small-scale** more sensitive to BW.

PROPAGATION ISSUES FOR CRN

Impact of propagation channel:

- **On sensing:**

- channel can **degrade** the signal level at the sensor.
- influence on $P\{FA\}$, $P\{MD\}$, and $P\{D\}$.
- in wide-band sensing, different frequencies may have different signal levels seen by the detector.

- **On transmission strategy:**

- which frequency to be assigned to which secondary user.
- i.e. In overlay approach: SU system needs accurate channel state from PU_{RX} to both PU_{TX} and SU_{RX} .

Parameters:

- Path loss:** reduction in the power density of the signal.
- Temporal Fading:** due to mobile or obstacle movement in space.
- Delay Spread:** difference in arrival time of different copies of the signal.

RECONFIGURATION, ADAPTATION, AND OPTIMIZATION

- CR should learn from previous states for intelligent and accurate adaptation(smartness).
- The **main part** of CR responsible for decision making is the Cognitive Engine (CE).
- CE deals with transmission and environmental parameters.
- The choice of parameters to be used depends on the objective of optimization.

Table.ref.[2]

Parameter Name	Description
Transmit power	Raw transmission power
Modulation type	Type of modulation format
Modulation index	Number of symbols for given modulation scheme
Bandwidth	Bandwidth of transmission signal in hertz
Channel coding rate	Specific rate of coding scheme
Frame size	Size of transmission frame in bytes
Time division duplexing	Percentage of transmit time
Symbol rate	Number of symbols per second

[2] Alexander M. Wyglinski, Ph.D., Maziar Nekovee, Ph.D., and Y. Thomas Hou, Ph.D, "Reconfiguration, Adaptation , and Optimization" Cognitive Radio Communications and Networks. Elsevier Inc, 2010, ch. 7, sec. 7.3, pp. 181

RECONFIGURATION, ADAPTATION, AND OPTIMIZATION

- “**fitness function**” used by CE and maps the parameters to objectives.
- Each **goal** In the table below has its specific mathematical function [3].
- “**fitness multi-objective function**” assigns a **weight** for each single objective:

$$f_{\text{multicarrier}} = w_1 \times (f_{\text{min_ber}}) + w_2 \times (f_{\text{max_tp}}) + w_3 \times (f_{\text{min_power}}) + w_4 \times (f_{\text{min_interference}}) + w_5 \times (f_{\text{max_spectralefficiency}})$$

Table.ref.[4]

Objective Name	Description
Minimize bit error rate	Improve the overall BER of the transmission environment
Maximize throughput	Increase the overall data throughput transmitted by the radio
Minimize power consumption	Decrease the amount of power consumed by the system
Minimize interference	Reduce the radio's interference contributions
Maximize spectral efficiency	Maximize the efficient use of the frequency spectrum

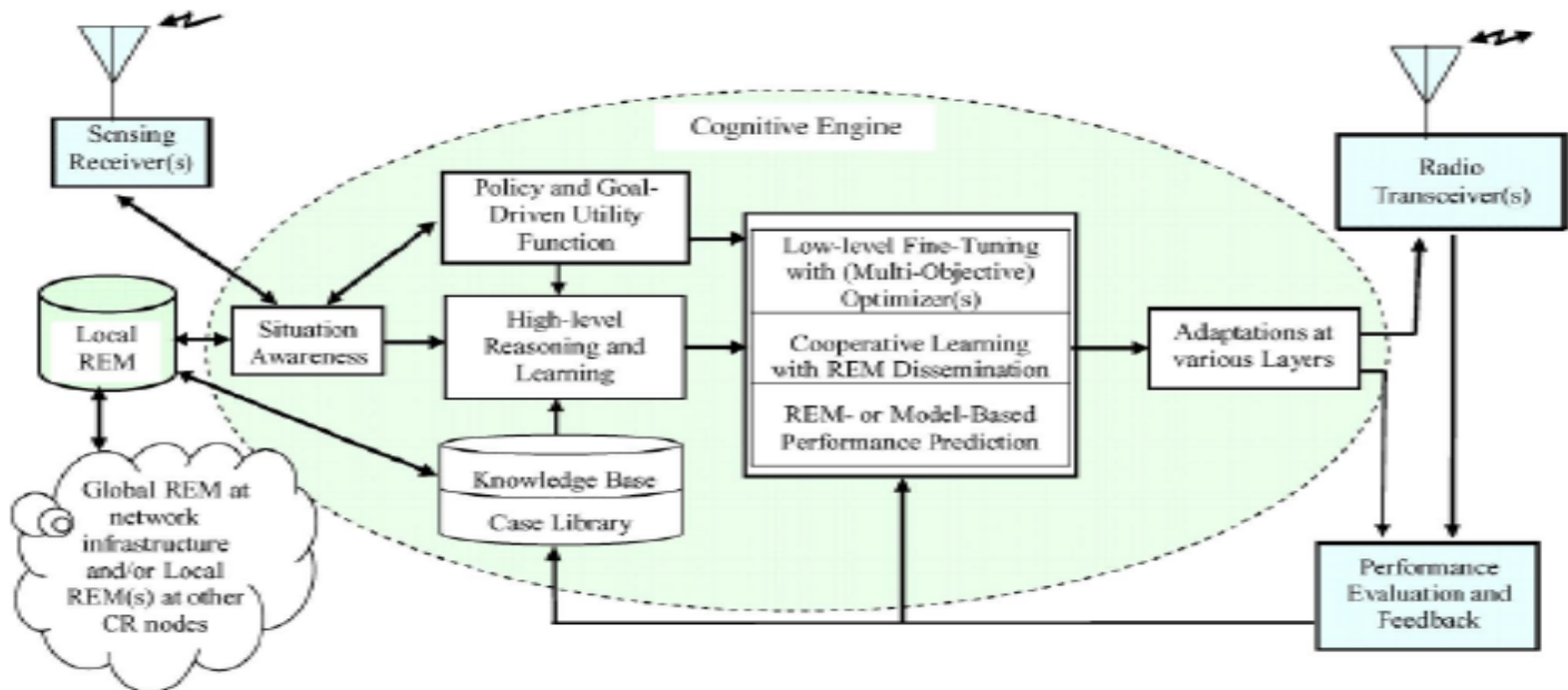
[3] Alexander M. Wyglinski, Ph.D., Maziar Nekovee, Ph.D., and Y. Thomas Hou, Ph.D, “Reconfiguration, Adaptation , and Optimization” Cognitive Radio Communications and Networks. Elsevier Inc, 2010, ch. 7, sec. 7.4, pp. 184

[4] Alexander M. Wyglinski, Ph.D., Maziar Nekovee, Ph.D., and Y. Thomas Hou, Ph.D, “Reconfiguration, Adaptation , and Optimization” Cognitive Radio Communications and Networks. Elsevier Inc, 2010, ch. 7, sec. 7.4, pp. 183

RECONFIGURATION, ADAPTATION, AND OPTIMIZATION

Cognitive Engine(CE)

- CE is the core of CR device.
- CE is responsible for decision making process based on past experience and current state.
- Several implementations exist for CE: Genetic algorithm, Rule-based system, and Case-based system.



RECONFIGURATION, ADAPTATION, AND OPTIMIZATION

Cognitive Engine-Genetic Algorithm

- Optimization solution is similar to genetic evolution (natural selection).
- Binary-strings (or other encoding) are used to represent the solutions.
- “good” strings split and combine between each other to form new solutions (like chromosomes structure) and others allowed to die.
- Advantage: needs low memory and can search in large population space.
- Disadvantage: large processing amount.

RECONFIGURATION, ADAPTATION, AND OPTIMIZATION

Cognitive Engine-Genetic algorithm

•The algorithm has **four stages**:

1. Initialization of population(For CR, Listing the parameters available).
2. Selection of a portion of population for new generation(randomly).
3. Reproducing new generation of solutions(objective of optimization).
4. Termination if one of the following holds:
 - if solution with minimum criteria found(optimization purpose).
 - fixed number of generations reached.
 - computation time reached.
 - no improvement.
 - any combination of them.

RECONFIGURATION, ADAPTATION, AND OPTIMIZATION

Cognitive Engine-Rule based system

- Optimization and adaptation is based on past experience stored in **database**.
- Formal rules are extracted from a set of observations (scientific model or local pattern in the data seen over the observation).
- It implements an **expert system** using **IF/THEN** statements.
- **Expert system is a software** that simulates the judgment and behavior of a human or an organization that has expert knowledge in a particular field.
- Has a disadvantage in management when the database becomes large.

RECONFIGURATION, ADAPTATION, AND OPTIMIZATION

Cognitive Engine-Case based system

- Use past experience and current state to make decision.
- It uses the individual case reasoning.
- A **case** is a piece of information representing an **experience**.
- A **case** consists of:
 - 1) case representation and indexing: info. format.
 - 2) case retrieval : For querying the DB.
 - 3) case evaluation and adaptation.
 - 4) case learning: experience learned from the case.
 - 5) case DB maintenance: update , add.

Then, each case has an **index and content** to describe it:

- 1) index: describe the context from where learned and where it can be used.
- 2) content: save the actual lessons learned.

RECONFIGURATION, ADAPTATION, AND OPTIMIZATION

Cognitive Engine-Case based system

- Similar cases grouped together in case library and then, organized in hierarchy.
 - This facilitates case retrieval.
- DB size doesn't increase linearly with the number of cases (i.e. update lesson).

THANK YOU 😊