COGNITIVE RADIO SPECTRUM MANAGEMENT – SENSING AND SHARING

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Key words: Cognitive Radio, Spectrum management, Spectrum sensing, Spectrum sharing, Wireless communications.

Due to the significant growth of the wireless users number, and of the wireless multimedia applications (which require an increasingly larger bandwidth), the radio spectrum has become overloaded. The solution proposed by Joseph Mitola III, in order to provide spectrum resources according to the user needs, was the Cognitive Radio (CR), which allows dynamically using of the existing spectrum. In the recent years the CR technology imposed itself as a very good solution to the increasing spectrum utilization. This technology proposes the development of a new radio type – a cognitive radio – endowed with intelligence that senses, shares, and uses the spectrum opportunities (SOP) of the preexisting wireless networks, the channels that are not used by the licensed users.

1. INTRODUCTION

The paper explains the Cognitive Radio (CR) main design idea that is to dynamically utilize the spectrum. Hereby, the spectrum users are divided into two categories: the primary users (PU) – the pre-existing wireless technology users, which are the holders of the licensed spectrum, and the CR users – the secondary users, that transmit on the PU licensed channels when they are inactive or the transmission is below a given interference threshold.

The content of the paper is presented along the next four sections. Thus, section 2 describes the CR concept and design features. Section 3 shortly presents the CR specific spectrum management function, and its main steps (spectrum sensing, sharing, and handover). Sections 4 and 5 detail the CR spectrum sensing function and sharing, respectively, with focus on the significance, classification. Also some basic methods to achieve spectrum sensing are here analyzed.

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Rev. Roum. Sci. Techn. – Électrotechn. et Énerg., **55**, *3*, p. 300–309, Bucarest, 2010

Finally, the last section concludes the paper, by underlying the ensued CR road until this moment and its lacks through a commercial form.

2. CR – A NEW TENDENCE IN WIRELESS COMMUNICATIONS

The CR technology eliminates the radio terminals that are specific to particular wireless technologies, and proposes an universal terminal, which should include all of the radio predecessors features into a single device, and, thus, an universal network (Fig. 1).

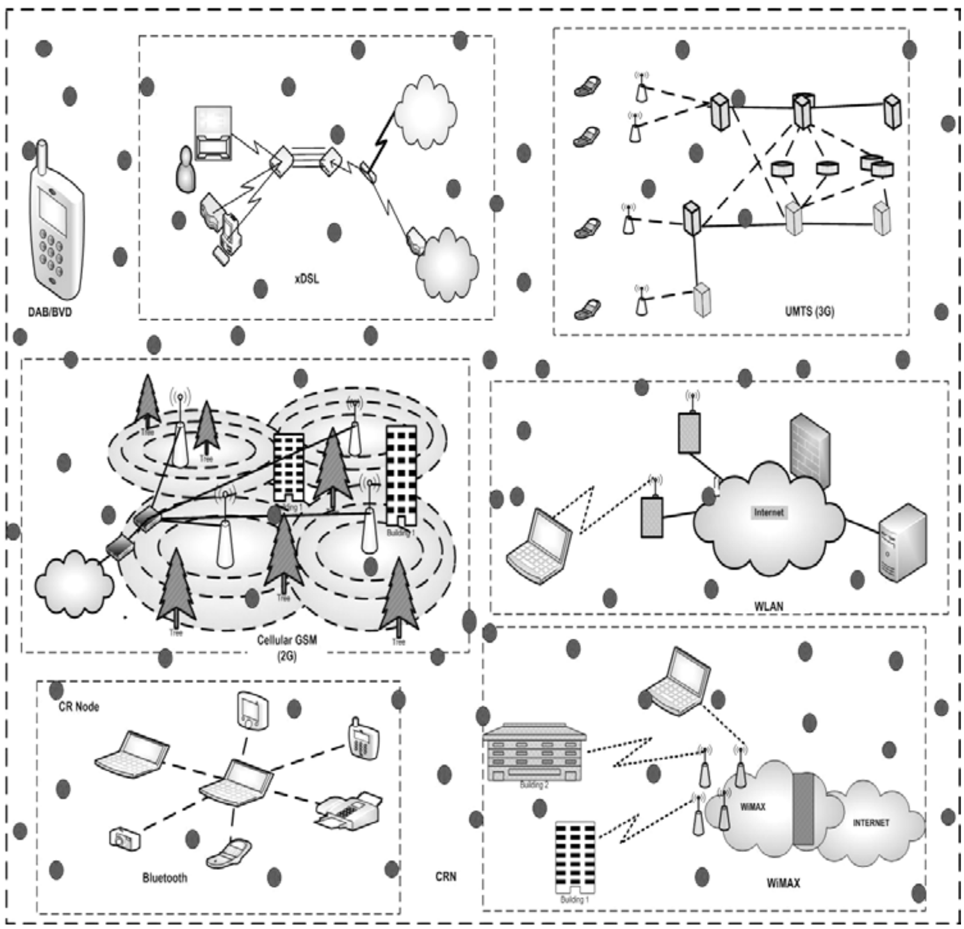

Fig. 1 – CRN architecture.

Cognitive radios are seen as intelligent agents, which possess conversation, reasoning and decision capabilities, and can become context aware, negotiate with the network, know theirs needs, and, after having all the necessary information, take the best decision regarding their activities.

Every cognitive radio should operate according to an intelligent algorithm, given by the "Cognition Cycle" [1], the main tasks of which are to: *observe, orient, plan, decide, act and learn* in a manner very similar to the human behavior.

The added functionality of CRs presume some modifications for the old radios operating manner and the possibility to integrate them in the existing architectures; this implies *new protocols*, which must include new rules/policies in order to make the communication work.

In the Table 1 it was attempted a brief summary of the properties that a CR terminal must perform.

3. SPECTRUM MANAGEMENT

In case of the CR technology, due to the dynamic spectrum utilization challenge, the spectrum management function presents new points against the old wireless spectrum management functions:

• **spectrum sensing –** the CRs capability to detect the availability of the licensed spectrum bands; • **spectrum sharing –** the manner in which the radio equipments use and share the available channels, regarding both the CR-PU and CR-CR cases; • **spectrum handover** – the frequency change for maintaining the transmission up (dynamically channel switching), due to the appearance of a PU or because of a transmission degradation.

4. SPECTRUM SENSING

By *spectrum sensing* is understood the CRs capability to detect the availability the spectrum bands.

The sensing operation may be seen like having three main parts (Fig. 2):

a. *signal detection*: does a signal exist on the sensed channel? (At this step there is no need to know the type of the existing signal);
b. *signal classification*: in case that a signal does exist, is this signal a PU signal? (The signal type is usually determined by extracting the sensed signal features);
c. *channel availability decision*: based on a certain criterion/rule and taking into consideration the precious sensing steps, it is determined if the channel is or not available?

Table 1

CR Properties

No.	CR Property	Short Description
1.	Sense the environment	CR is able to observe the environment and its neighbor behavior, and, based on the collected results, to decide its configuration and actions.
2.	Use of the spectrum holes	Capacity to dynamically utilize the sensed spectrum holes of the preexisting systems. In order to transmit, a CR must be able to see the used and unused spectrum bands, the so called "white spaces" (in other words, to notice if the primary users are using or not theirs bands for transmission). If the legacy radio is not transmitting, then the CR could use the corresponding band according to some constraints – radio protocols. *Note:* the first standard to describe the possibility to utilize the "white spaces" in the TV frequency spectrum, without interfering with the incumbent users, started to develop using the cognitive radio paradigm – IEEE 802.22.
3.	Adaptation to the changes	CR must stop the transmission or modify its configuration parameters in response to the environment changes.
4.	Interoperability with the preexisting systems	Possibility to interoperate/cooperate with the existing systems and architectures, without the need of a change.
5.	Interoperability with other CR devices	CR is able to communicate with other CR devices in order to share the spectrum holes, according to a medium access scheme, and the sensed information.
6.	Connectivity	CR must provide connectivity in scarce spectrum areas, especially in the rural areas.
7.	Support for all the application types	All the human life domains: education, telehealth, community, office, home, positions and localizations, and, especially, emergency care, military, public safety communications, which implies the strong need of security issues design in the CR development [2].
8.	Secure and trusted CR operations	By "secure and trusted" it is understood protection from physical damage, authentication etc., in order to respond at the new threats and challenges, given by this new way of spectrum use.

Each CR terminal has endowed the sensing capabilities and can perform the spectrum sensing function. According to a CR user possibility to share or not its sensing results with other CRs, it can be defined a first possibility to classify the sensing function (Fig. 2).

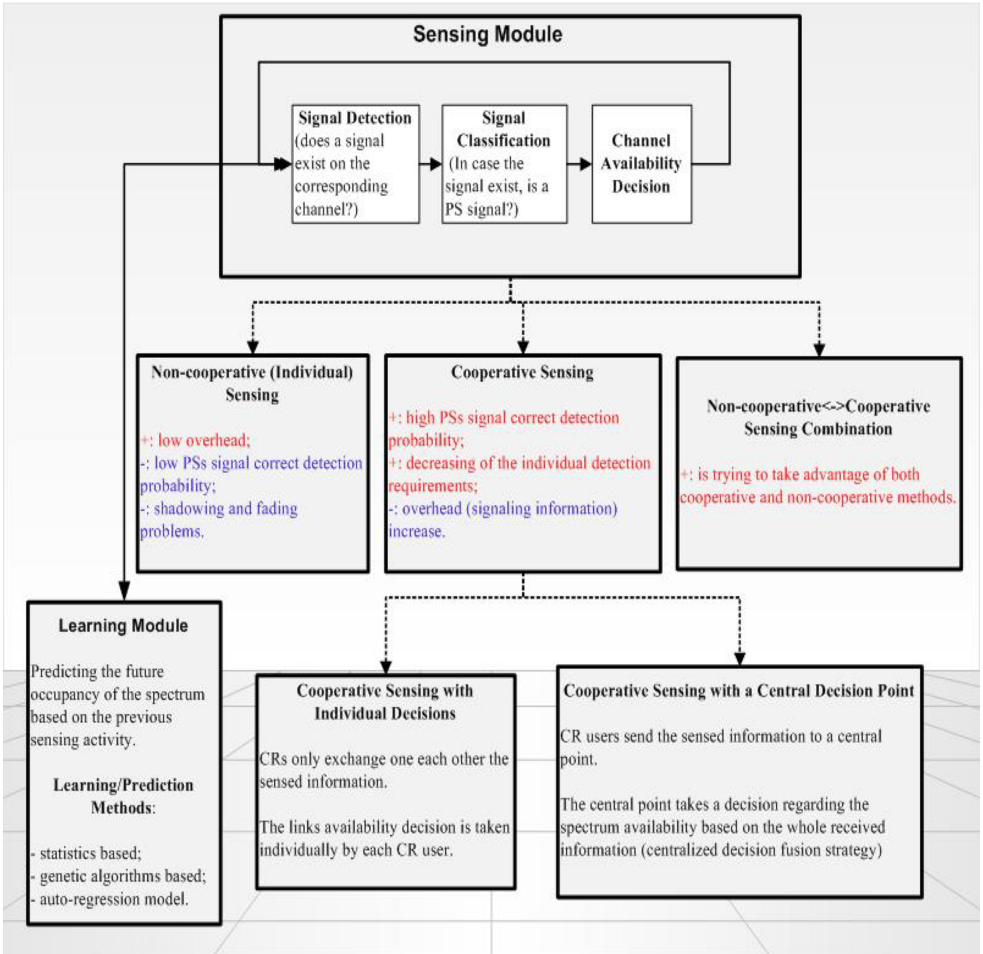

Fig. 2 – Sensing function.

1. *Non-Cooperative sensing* means that each CR user is individually performing the sensing function, do not share the channel availability obtained results with other users, and take the final link availability decision based on its sensing activity only. The non-cooperative manner of sensing presents a big disadvantage in a hidden terminal case.
2. *Cooperative sensing* means that each CR user is individually performing the sensing function, but, unlike the non-cooperative case, the CR is sharing its results with all the CR neighbors; thus, all the results will be aggregated, and

the final link availability decision will be taken based on the results conglomeration [3, 4].

Depending on the final decision regarding the links availability, the cooperative case presents two instances (Fig. 2):

2.1. *Cooperative sensing with individual decisions*: each CR takes the final decision in a individual form, but also taking into account the sensed results of its neighbors;

2.2. *Cooperative Sensing with centralized decisions* (correlation between nodes): the CRs are using the individual sensing techniques, but the channel availability decision is not individual; their sensing results are collected by a unique entity that will take the channels availability decision based on the individually received results and will inform all the CRs.

Different techniques (analog, digital, and network processing techniques) were proposed to analyze the spectrum sensing possibility; the best results were obtained when using signal processing (matched filter, energy detection, and, especially, cyclo-stationary feature detection).

In this context, Table 2 synthesizes the advanced spectrum sensing methods, until this moment. The below presented techniques are individual, answering at the non-cooperative sensing needs.

In order to also respond at the cooperative sensing case, it must be also addressed a *cooperative principle*: *a soft combination of the observed values* (*i.e.* a fuzzy collaborative spectrum sensing scheme, that is a combination of the different CRs distributed sensing results).

5. SPECTRUM SHARING

Spectrum sharing is the second step of the spectrum management operation and determines the manner in which the radio equipments use and share the previous detected available channels, regarding both the CR-PU and CR-CR cases:

- the policy according to a CR may employ the PU spectrum;
- the settlements according to which several CRs are competing for the same spectrum resources.

Corresponding with the priority level of accessing the radio spectrum, the spectrum sharing can be classified in different categories [15] (Fig. 3):

- *horizontal spectrum sharing* – the radio devices have equal rights to access the spectrum;
- *vertical spectrum handover* – different priorities to access the spectrum

Table 2

Sensing Methods

Sensing – Method Types	**Method Sub – Types**	**Method Examples**	**Remarks**
Signal Detection	General	energy based	The detected power level (of the sensed channel) is compared with a given threshold in order to establish if a signal exists or not on that channel [5].
		preamble detection	Detecting the preamble bits/synchronization bits on the sensed channel means that the signal do exist [6].
		pilot based	In the telecommunication field, the pilot signal is usually used as a reference, and its frequency differ from one type of communication technique to another, allowing the signal detection [5].
		cyclo-stationarity based	Most of the modulated signals have cyclic properties varying in time; identifying the cyclic properties means detecting the signal type on the sensed channel [7].
		covariance based	A way to compare the sensed signal with a known signal until a match is found [8].
		statistics based	Spectrum usage prediction [9].
	OFDM specific	fundamental rate based	Tracking fundamental signal rate of the OFDM (Orthogonal Frequency Division Multiplexing) primary systems signal [10].
		OFDM cyclic prefix	Cyclic property of OFDMA signal (Neyman-Pearson criterion) [10].
		sub-carrier spacing	For an OFDM signal, in order to maintain the sub-carries orthogonality, the sub-carrier spacing must be $\Delta f = 1/T$, where T, *i.e.* the seconds, is the useful symbol duration [11].
		guard interval properties	The guard interval between the OFDM symbols in order to eliminate the inter-symbol interference [11].
Signal Classification		digital modulation classification (using the waveforms features)	Digital modulation examples: PSK – Phase Shift Keying (change the phase of the reference signal), FSK – Frequency Shift Keying (change the frequency of the reference signal), ASK – Amplitude Shift Keying (change the amplitude of the reference signal) [12].
		differentiate signal from noise	The main idea is that for two independent variables the covariance is zero (they are uncorrelated) – this will be the case of noise and PU signal [13].
Spectrum Holes Availability		likelihood ratio test	A likelihood test is a statistical test to choose between two hypotheses, in this case between the PUs presence /absence in the sensed channel hypothesis [14].

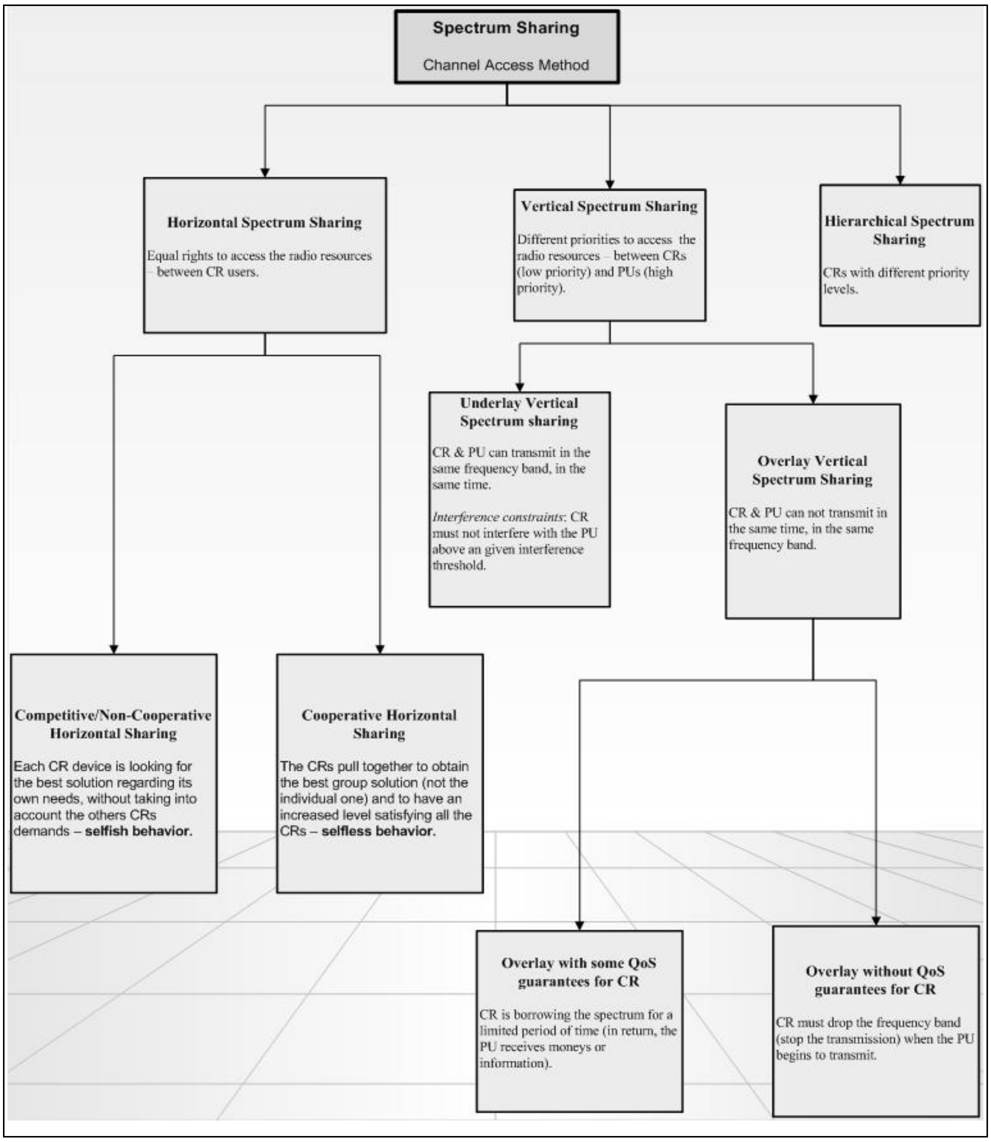

Fig. 3 – Sharing function.

between PUs (high priority) and CR users (low priority);

- *hierarchical spectrum sharing* – several priorities levels of accessing the spectrum (the CRs that are competing for the same available spectrum bands can have different priorities).The hierarchical access is an elevated variant for the vertical spectrum sharing.

In turn, each of the spectrum sharing variants can present a sub-classification.

Thus, in *horizontal spectrum sharing*, taking into account the CRs cooperation presence/absence regarding the sensed spectrum utilization and repartition, two categories can be distinguished:

- *non-cooperative horizontal sharing*: each CR device is looking for the best solution as regards to its own needs, without taking into account the other CRs demands (selfish behavior);
- *cooperative horizontal sharing*: the CRs pull together to obtain the best group solution (not individual one) and to have a raised level of satisfying all the CRs (selfless behavior).

In the *vertical spectrum sharing case***,** two main approaches can be identified:

- *underlay vertical spectrum approach*: the CR users are allowed to transmit in the same frequency band with the PUs as long as they are not generating interference to the PUs above a pre-established interference threshold;
- *overlay vertical spectrum approach*: CR users are not allowed to transmit in the same band and in the same time with the PUs. Two overlay sub-cases were identified:
    - *overlay with some CR QoS (Quality of Service) guarantees*: CRs are borrowing the PUs spectrum bands for a given period of time and the PUs may respect or not this borrowing period; in return, PUs are receiving a corresponding price or some information.
    - *overlay without QoS guarantees for CRs*: CR users must stop the transmission in the opportunistically occupied band when the PUs start to transmit.

For a good vertical sharing is necessary to have a good defined admission control function for CRs in order to utilize or not the PU channels.

6. CONCLUSIONS

The CR study implies a big number of different disciplines such as: signal processing, information theory, communication engineering, game theory, bio-inspired behaviors, human behaviors, programming, artificial intelligence, economy, etc. – so the CR study is a rather "inter-disciplinary" field [16], rendering the study very difficult.

We can conclude that CR is now a good delineated technology, with particularities in the OSI (Open Systems Interconnection) stack, especially regarding the spectrum sensing and sharing capabilities, and that a lot of solutions to achieve a functional CR technology were proposed, but the need *to integrate* them into a workable CR device (and even to improve them) still remains open. Also the necessity appears for tighter cross-layer approach between the layers; the first steps were made, since Virginia Tech presented such a test-bed, that allows the development of simultaneous CR solutions for different layers and test them [17].

CR technology can also be regarded like a "liaison" between different wireless technologies, making possible to integrate all these in a large functional network. Consequently, CR will become one of the first steps to a universal network.

Received on May 21, 2010

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