

Cognitive Radio: An Intelligent Wireless Communication System

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ABSTRACT: Cognitive radio (CR) is the enabling technology for supporting dynamic spectrum access: the policy that addresses the spectrum scarcity problem that is encountered in many countries. The spectrum sensing problem has gained new aspects with cognitive radio networks. Radio spectrum is the most valuable resource in wireless communication. Cognitive radio is a new concept of reusing licensed spectrum in an unlicensed manner. Cognitive radio is motivated by recent measurements of spectrum utilization, showing unused resources in frequency, time and space. The spectrum must be sensed to detect primary user signals, in order to allow cognitive radios in a primary system. The fundamental problem of spectrum sensing is to discriminate samples that contain only noise from samples that contain a very weak signal embedded in noise. We derive detectors that exploit known structures of the signal, For the cases of an OFDM modulated signal and an orthogonal space-time block coded signal. We derive optimal detectors, in the Neyman-Pearson sense, for a few different cases when all parameters are known. Moreover we study detection when the parameters, such as noise variance, are unknown. We propose solutions the problem of unknown parameters. More specifically, we investigate spectrum reuse of geographical spectrum holes in a frequency planned primary network. System performance is measured in terms of the achievable rate for the cognitive radio system. The limited available spectrum and the inefficiency in the spectrum usage necessitate a new communication technology, referred to as cognitive radio (CR) networks. Cognitive radios are intelligent devices with ability to sense environmental conditions and can change its parameters to the requirements to get the optimized performance at the individual nodes or at network level. Thus, CR is widely regarded as one of the most promising technologies for future wireless communications.

KEYWORDS: cognitive radio ,ofdm, spectrum sensing,wsn,CRN

I. INTRODUCTION

In wireless communication systems, the right to access the spectrum is generally defined by frequency, transmission power, spectrum owner (i.e., licensee), type of use, and the duration of license. Usually, a license is assigned to one licensee, and the use of spectrum by this licensee must be conformed to the specification in the license. In the older spectrum licensing schemes, the license cannot change the type of use or transfer the right to other licensees. Moreover, the radio spectrum is licensed for larger regions and generally in larger chunks. All these factors in the current model for spectrum allocation and assignment limit the use and result in low utilization of the frequency spectrum. Because the existing and new wireless applications and services are demanding for more transmission capacity and more data transmission hence, the utilization of the radio spectrum needs to be improved. To improve the efficiency and utilization of the radio spectrum, the above mentioned limitations should be ended by modifying the spectrum licensing scheme and adopting a dynamic spectrum management model. The basic idea is to make spectrum access more flexible by allowing the unlicensed users to access the radio spectrum under certain conditions and restrictions. Because the traditional wireless systems were designed to operate on a dedicated frequency band, they are not able to utilize the improved flexibility provided by this spectrum licensing scheme. Therefore, the concept of cognitive radio (CR) emerged, the main goal of which is to provide adaptability to wireless transmission through dynamic spectrum access(DSA) so that the utilization of the frequency spectrum can be enhanced without losing the

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 3, March 2016

benefits associated with static spectrum allocation. The CR is a “smarter radio” in the sense that it can sense channels that contain signals from a large class of heterogeneous devices, networks, and services.

On the basis of this sensing, the radio will implement sophisticated algorithms to share the limited bandwidth channel with other users in order to achieve efficient wireless communication. In this way, the CR concept generalizes the idea of multiple access involving devices in a single homogeneous system to multiple access among devices in different radio spectrums using different radio transmission techniques and hence different systems (i.e., inter-system multiple access as opposed to the more traditional intra-system multiple access), which have different priorities in accessing the spectrum. In present day communication wireless communication has become the most popular communication. Because of this growing demand on wireless applications has put a lot of constraints on the available radio spectrum which is limited and precious.

In fixed spectrum assignments there are many frequencies that are not being properly used. So cognitive radio helps us to use these unused frequency bands which are also called as “White Spaces”. This is a unique approach to improve utilization of radio electromagnetic spectrum. In establishing the cognitive radio there are 4 important methods. In this paper we are going to discuss about the first and most important method to implement cognitive radio i.e., “spectrum sensing”.

II. COGNITIVE RADIOS

The term "Cognitive Radio" (CR) was coined by Joe Mitola in 1999-2000. The term was intended to describe intelligent radios that can autonomously make decisions using gathered information about the RF environment through model-based reasoning, and can also learn and plan according to their past experience. Clearly, such a level of intelligence requires the radio to be self-aware, as well as content and context-aware. Moreover, Haykin defines CR as a radio capable of being aware of its surroundings, learning, and adaptively changing its operating parameters in real-time with the objective of providing reliable anytime, anywhere, and spectrally efficient communication.

The term CR is defined in as follows: “Cognitive radio is an intelligent wireless communication system that is aware of its ambient environment. A cognitive radio transmitter will learn from the environment and adapt its internal states to statistical variations in the existing RF stimuli by adjusting the transmission parameters (e.g., frequency band, modulation mode, and transmission power) in real-time and on-line manner.” This definition essentially captures the fundamental concept behind CR. A cognitive radio network (CRN) enables us to establish communications among CR nodes/users. The communication parameters can be adjusted according to the change in the radio environment, topology, operating conditions, or user requirements.

Two main objectives of the CR are to improve the utilization of the frequency spectrum and to achieve the highly reliable and highly efficient wireless communications. The term CR is defined in as follows: “Cognitive radio is an intelligent wireless communication system that is aware of its ambient environment. A cognitive radio transmitter will learn from the environment and adapt its internal states to statistical variations in the existing RF stimuli by adjusting the transmission parameters (e.g., frequency band, modulation mode, and transmission power) in real-time and on-line manner.” This definition essentially captures the fundamental concept behind CR.

A cognitive radio network (CRN) enables us to establish communications among CR nodes/users. Two main objectives of the CR are to improve the utilization frequency spectrum and to achieve the highly reliable highly efficient wireless communications. Cognitive radios are self-aware and intelligent device switch can sense the changing environmental conditions and can change their parameter like frequency, modulation techniques, coding techniques, power etc. according to changing statistical communication environmental thus resulting in efficient utilization of available resources.

Cognitive radios must be intelligent enough to learn and decide about their operating parameters and could change their transmission and reception parameters to meet performance requirements and maximize Qos. Operations of the cognitive radio are controlled by the Cognitive engine (CE). The cognitive engine performs the tasks of sensing, analysis, learning, decision making and reconfiguration. Cognitive radio networks consist of two types of users, primary (licensed) and secondary (unlicensed or cognitive) users. Licensed users have higher priority for the usage of the licensed spectrum. On the other hand unlicensed users can opportunistically communicate in licensed spectrum by changing their communication parameters in an adaptive way when spectrum holes are available.

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Vol. 5, Issue 3, March 2016

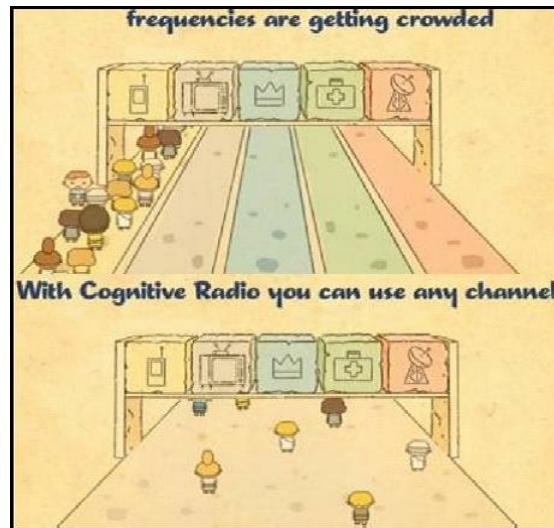


Figure No. 1: Frequency utilization in Cognitive Radio Networks.

Cognitive radio-based DSA or sharing has basically two major flavours, that is, horizontal spectrum sharing and vertical spectrum sharing. In the former case, all users/nodes have equal regulatory status, whereas in the latter case all users/nodes do not have equal regulatory status. In vertical spectrum sharing, there are primary (i.e., licensed) users and secondary (i.e., unlicensed) users, and the secondary users opportunistically access the spectrum without affecting the primary users' performances. Horizontal spectrum sharing can be between homogeneous networks (e.g., IEEE 802.11a operating in the 5-GHz Unlicensed National Information Infrastructure band) or between heterogeneous networks (e.g., coexistence between IEEE 802.11b and 802.15.1 [Bluetooth] networks). When all the networks in a heterogeneous environment have cognitive/adaptive capabilities (i.e., all coexisting networks have equal incentives to adapt), it is referred to as symmetric sharing. On the other hand, when there is one or more network without cognitive/adaptive capabilities (e.g., coexistence of legacy technology with CR technology), this is referred to as asymmetric spectrum sharing. One example of this is the coexistence of high speed IEEE 802.11 networks with low-power IEEE 802.15.4 networks. DSA in vertical spectrum sharing is referred to as opportunistic spectrum access. This opportunistic spectrum access is the method for the secondary user to operate within a frequency band that is designated to the primary user.

The concept of Cognitive Radio (CR) appeared as a new paradigm in 1999 as an extension of Software Defined Radio (SDR). It describes the situation where intelligent radio devices and associated network entities communicate in such a manner that they are able to adjust their operating parameters according to the needs of the user/network, and learning from experience at the same time. Since then, there has been a significant amount of effort in the research community on CR-related topics. Standardization activities on Cognitive Radio Systems (CRS) (including TV White Spaces—TVWS) have also been initiated and progressed in many standardization bodies. Almost all regulatory bodies in the USA, Europe and Asia-Pacific regions have acknowledged the importance of CRS on shaping the way spectrum is allocated. The figure below shows the main building blocks for the deployment of a Cognitive Radio system. In cross layer design of cognitive radio all layers extract information coming from the PHY layer and exchange it to optimize the QoS expectations of the application. CR senses the environment using information from physical and MAC layer. Present protocols designed for the physical and MAC layers for static spectrum allocation cannot be used for the CR based networks. For CR based networks the MAC layer protocols must have the ability to utilize the information from the physical layer. It also helps the MAC layer in assigning the resources to radio nodes. The decisions will be done on the basis of information provided by the Physical layer.

2.1 Cognitive Radio Requirements

One of the main goals targeted with cognitive radio is to utilize the existing radio resources in the most efficient way. To ensure the optimum utilization, cognitive radio requires a number of conditions to be satisfied. The primary cognitive radio requirements are (a) negligible interference to licensed systems, (b) capability to adapt itself to various

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link qualities,(c) ability to sense and measure critical parameters about the environment, channel, etc.(d) ability to exploit variety of spectral opportunity,(e) flexible pulse shape and bandwidth,(f) adjustable data rate, adaptive transmit power, information security, and limited cost. The aim of Cognitive Radio is usage of frequency bands that are owned by their licensed users. Therefore, one of the most significant requirements of cognitive radio is that the interference caused by cognitive devices to licensed users remains at a negligible level. One of the main features of the cognitive radio concept is that the targeted frequency spectrum is scanned periodically in order to check its availability for opportunistic usage. According to the results of this spectrum scan, the bands that will be utilized for cognitive communication are determined. Since at different times and locations the available bands can vary, cognitive radio is expected to have a high flexibility in determining the spectrum it occupies.

2.2 Physical architecture of the cognitive radio

A generic architecture of a cognitive radio transceiver is shown in Figure no. 2. The main components of a cognitive radio transceiver are the radio front-end and the baseband processing unit. Each component can be reconfigured via a control bus to adapt to the time-varying RF environment. In the RF front-end, the received signal is amplified, mixed and A/D converted. In the baseband processing unit, the signal is modulated/demodulated and encoded/decoded. The baseband processing unit of a cognitive radio is essentially similar to existing transceivers. However, the novelty of the cognitive radio is the RF front-end. Hence, next, we focus on the RF front-end of the cognitive radios.

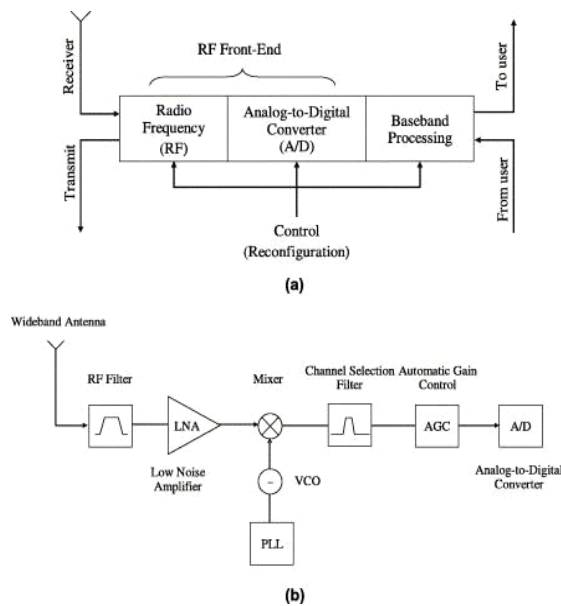


Figure No. 2: Physical architecture of the cognitive radio (a) Cognitive radio transceiver and (b) wide band RF/ analog front-end architecture.

The novel characteristic of cognitive radio transceiver is a wideband sensing capability of the RF front-end. This function is mainly related to RF hardware technologies such as wideband antenna, power amplifier, and adaptive filter. RF hardware for the cognitive radio should be The novel characteristic of cognitive radio transceiver is a wideband sensing capability of the RF front-end. This function is mainly related to RF hardware technologies such as wideband antenna, power amplifier, and adaptive filter. RF hardware for the cognitive radio should be capable of tuning to any part of a large range of frequency spectrum. Also such spectrum sensing enables real-time measurements of spectrum information from radio environment. Generally, a wideband front-end architecture for the cognitive radio has the following structure as shown in Figure no. 2. The components of a cognitive radio RF front-end are as follows:

- 1. RF filter:** The RF filter selects the desired band by bandpass filtering the received RF signal.

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2. **Low noise amplifier (LNA):** The LNA amplifies the desired signal while simultaneously minimizing noise component.
3. **Mixer:** In the mixer, the received signal is mixed with locally generated RF frequency and converted to the baseband or the intermediate frequency (IF).
4. **Voltage-controlled oscillator (VCO):** The VCO generates a signal at a specific frequency for a given voltage to mix with the incoming signal. This procedure converts the incoming signal to baseband or an intermediate frequency.
5. **Phase locked loop (PLL):** The PLL ensures that a signal is locked on a specific frequency and can also be used to generate precise frequencies with fine resolution.
6. **Channel selection filter:** The channel selection filter is used to select the desired channel and to reject the adjacent channels. There are two types of channel selection filters. The *direct conversion receiver* uses a low-pass filter for the channel selection. On the other hand, the *superheterodyne receiver* adopts a bandpass filter.
7. **Automatic gain control (AGC):** The AGC maintains the gain or output power level of an amplifier constant over a wide range of input signal levels. In this architecture, a wideband signal is received through the RF front-end, sampled by the high speed analog-to-digital (A/D) converter, and measurements are performed for the detection of the licensed user signal. However, there exist some limitations on developing the cognitive radio front-end. The wideband RF antenna receives signals from various transmitters operating at different power levels, bandwidths, and locations. As a result, the RF front-end should have the capability to detect a weak signal in a large dynamic range. However, this capability requires a multi-GHz speed A/D converter with high resolution. The requirement of a multi-GHz speed A/D converter necessitates the dynamic range of the signal to be reduced before A/D conversion. This reduction can be achieved by filtering strong signals. Since strong signals can be located anywhere in the wide spectrum range, tunable notch filters are required for the reduction. Another approach is to use multiple antennas such that signal filtering is performed in the spatial domain rather than in the frequency domain. Multiple antennas can receive signals selectively using beam forming techniques.

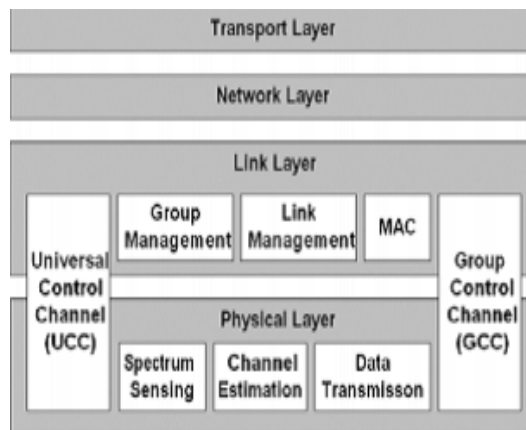


Figure No. 3: General ISO/OSI Model for Cognitive Radio

As the need of wireless communication applications are increasing the available Electromagnetic Spectrum band is getting crowded day by day. According to many researches it has been found that the allocated spectrum (licensed spectrum) is not utilized properly because of static allocation of spectrum. It has become most difficult to find vacant bands either to set up a new service or to enhance the existing one. In order to overcome these problems we are going for “Dynamic Spectrum Management” which improves the utilization of spectrum. Cognitive Radio works on this dynamic Spectrum Management principle which solves the issue of spectrum underutilization in wireless communication in a better way. This radio provides a highly reliable communication. In this the unlicensed systems (Secondary users) are allowed to use the unused spectrum of the licensed users (Primary users). Cognitive radio will change its transmission parameters like wave form, protocol, operating frequency, networking etc based on the interaction with environment in which it operate. Figure no. 4 shows the Dynamic Spectrum Access in Cognitive Radio.

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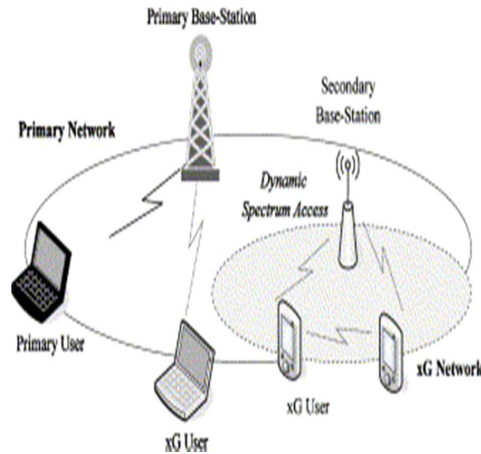


Figure No. 4: Dynamic Spectrum Access

Cognitive radio has four major functions. They are Spectrum Sensing, Spectrum management, Spectrum Sharing and Spectrum Mobility. Spectrum Sensing is to identify the presence of licensed users and unused frequency bands i.e., white spaces in those licensed bands. Spectrum Management is to identify how long the secondary users can use those white spaces. Spectrum Sharing is to share the white spaces (spectrum hole) fairly among the secondary users. Spectrum Mobility is to maintain unbroken communication during the transition to better spectrum. In terms of occupancy, sub bands of the radio spectrum may be categorized as follows:

- A) *White spaces*: These are free of RF interferers, except for noise due to natural and/or artificial sources.
- B) *Gray spaces*: These are partially occupied by interferers as well as noise.
- C) *Black spaces*: The contents of which are completely full due to the combined presence of communication and (possibly) interfering signals plus noise.

Figure no. 5 shows the White Spaces and used Frequencies in Licensed Spectrum.

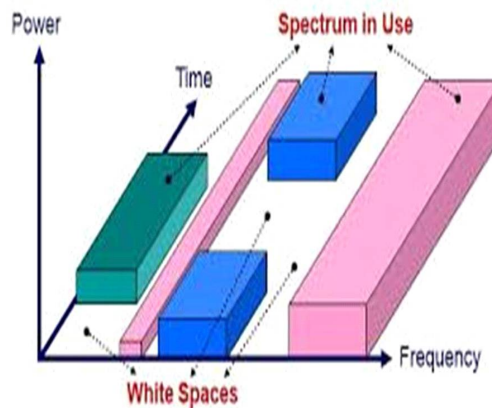


Figure No. 5: Illustration of White Spaces in Licensed Bands

When compared to all other techniques, Spectrum Sensing is the most crucial task for the establishment of cognitive radio based communication mechanism. In order to achieve these objectives, cognitive radio is required to adaptively modify its characteristics and to access radio spectrum without causing excessive interference to the primary licensed users. Cognitive cycle of cognitive radio operation as secondary radio system is shown in Figure no.6. Steps of the cognitive cycle are: spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility.

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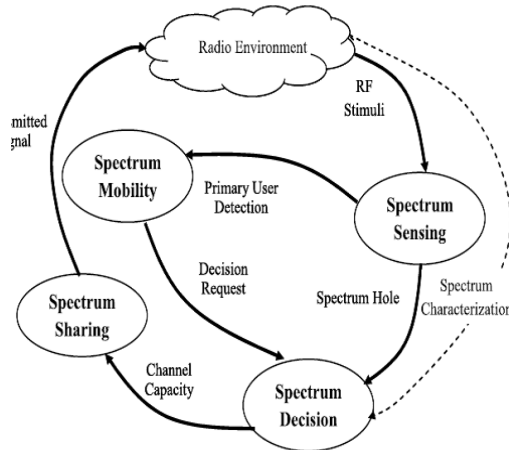


Figure No. 6: Cognitive cycle of cognitive radio

Spectrum sensing is active spectrum awareness process where cognitive radio monitors its radio environment and geographical surroundings, detect usage statistics of other primary and secondary users and determine possible spectrum space holes. Spectrum sensing can be done by one cognitive radio, by multiple cognitive radio terminals or by independent sensing network exchanging information in a cooperative way which improves overall accuracy. Spectrum decision: Based on spectrum sensing information cognitive radio selects when to start its operation, operating frequency and its corresponding technical parameters. Cognitive radio primary objective is to transfer as much as possible information and to satisfy required quality of service, without causing excessive interference to the primary users. Additionally, cognitive radio may use data from regulatory database and policy database in order to improve its operation and outage statistics. Spectrum sharing: Since there is number of secondary users participating in usage of available spectrum holes, cognitive radio has to achieve balance between its self-goal of transferring information in efficient way and altruistic goal to share the available resources with other cognitive and noncognitive users. This is done with policy rules determining cognitive radio behaviour in radio environment. Spectrum mobility: If primary user starts to operate, cognitive radio has to stop its operation or to vacate currently used radio spectrum and change radio frequency. In order to avoid interference to primary licensed user this function has to be performed in real time, therefore cognitive radio has to constantly investigate possible alternative spectrum holes. Cognitive radio is developing radio concept founded on software defined radio, digital signal processing and artificial intelligence. Aim of the cognitive radio is to use natural resources efficiently including space, frequency, time, and transmitted energy by sensing the environment and adaptive transmission without causing excessive interference to the primary licensed users. The performance requirements for cognitive radio system are: reliable spectrum hole and primary user detection, accurate link estimation between nodes, fast and accurate frequency control and power control method that assures reliable communication between cognitive radio terminals and non-interference to primary users.

III. SPECTRUM AWARENESS

One of the most important features of the cognitive radio is the ability to acquire, measure, sense, learn and be aware of the radio's operating environment in order to recognize spectrum space opportunities and efficiently use them for adaptive transmission. This task is very demanding since cognitive radios are in a way blind and they cannot see other radios. Their awareness of the outside world is founded on information obtained from others or their own "hearing". Imagine that a blind man arrives at a crossing and tries to conclude weather the road is free or not to go based only on his hearing. This functionality of cognitive radio is exercised through spectrum awareness. Spectrum awareness can be classified as passive and active awareness (or also called spectrum sensing).

Figure no. 7 shows basic classification of spectrum awareness methodologies for cognitive radio. In the passive awareness radio spectrum information is received from outside world like from primary communications system, from server, from centralized database, or predefined policy set. In this approach relevance of data in space and

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time is critical and additional communication channel is needed for acquiring information. While leading to simplified secondary transceivers, these methods require some modifications to the legacy primary system, additional data acquisition, data storage resources, data management system, and additional network capacity. Generally, passive awareness results in rather static secondary usage without optimally exploiting spectrum space opportunities.

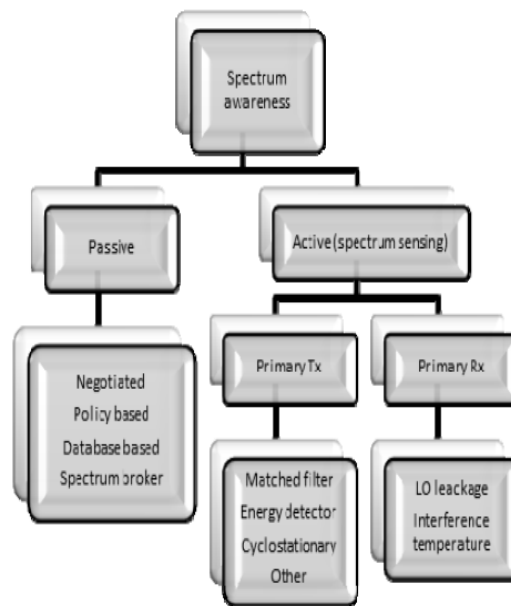


Figure No. 7: Spectrum awareness classification

In active awareness secondary users actively sense the radio environment and adapt their transmissions based on the measurements. In non-cooperative model secondary users make their decisions independently based on the observations about the spectrum environment. In cooperative situation local measurements will be combined and signalled to all secondary users before decisions about spectrum use are made. Active awareness is more complex and hardware demanding, but generally it results in improved secondary users spectrum usage statistics compared to spectrum usage based on passive awareness. Cognitive radio systems may employ either one or both forms of awareness, thus the discussed approaches should not be viewed as mutually exclusive. In systems based on negotiated spectrum use the primary system announces secondary users about the allocated frequencies and the available spectrum opportunities using spectrum beacons. Negotiation is usually centralized and includes determination of geographical, temporal, technical, financial, service quality and interference constraints and conditions. In the policy based approach, the national regulatory agency identifies a licensed band of the radio spectrum where use is low or the band is used with a deterministic pattern. The regulatory agency assigns a set of policies that provide rules and constraints concerning how to use this radio spectrum for secondary use. Secondary devices repeatedly seek for updates of policies that are relevant for their regulatory domain and update their information bases. After updating information, secondary users adapt their transmission parameters like frequency and power to meet predefined policies.

IV. CONCLUSION

Radio system founded on cognitive radio technology is challenging and promising concept, leading to new directions in developments of wireless communications and leap progress in radio spectrum usage efficiency. It is seen as a groundbreaking and founding technology of future wireless systems. Nevertheless, cognitive radio is not a magic wand which will instantly solve radio spectrum scarcity problems, liberate all the frequency bands and abrogate radio spectrum regulation. As we look in the future, we see that cognitive radio has the potential for making a significant

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difference in the way how the radio spectrum can be accessed and used by wireless systems. However, cognitive radio is still in its infancy. Development of cognitive radio systems are cross related and dependent to developments in many different technical and non-technical areas like: software defined radio, digital signal processing, artificial intelligence and machine learning, but also bioinspired intelligence, social group behaviour, economical studies, etc. Emergence of full cognitive radio capable radio system is still years, even decades far away from practical realization. What we currently see is: many research advances in the area and gradual implementation of various cognitive radio related technological concepts in modern communication systems. Even if only thirty percent of predicted cognitive radio system functionalities will be realized in radio devices in the forthcoming years, this would bring significant advances to future wireless communications systems. In this article, we have presented motivation for developments of opportunistic spectrum access, an overview of cognitive radio systems and major technical and research issues in cognitive radio. Given the complexity of the topic and the diversity of existing technical approaches, our presentation is by no means exhaustive. We hope that this article provides a glimpse of the technical challenges and exciting research activities in the cognitive radio systems.

REFERENCES

- [1] ITU Radio Regulations, International Telecommunication Union, Genève, 2008.
- [2] Federal Communications Commission, "Facilitating Opportunities for Flexible, Efficient and Reliable Spectrum Use Employing Cognitive Radio Technologies", notice of proposed rulemaking and order, FCC 03-322, December 2003.
- [3] Federal Communications Commission Spectrum Policy Task Force, "Report of the Spectrum Efficiency Working Group", November 2002.
- [4] Shared Spectrum Company, "Spectrum Occupancy Measurements", 2005, retrieved from www.sharedspectrum.com/measurements on 27/10/2009.
- [5] K. N. Steadman, A. D. Rose, and T. T. N. Nguyen, "Dynamic Spectrum Sharing Detectors", In Proc. of IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2007), Dublin, Ireland, April 2007, pp. 276-282.
- [6] M. Wellens and P. Mähönen, "Lessons Learned from an Extensive Spectrum Occupancy Measurement Campaign and a Stochastic Duty Cycle Model", Proc. of Trident Com 2009, Washington D.C., USA, April 2009, pp. 1-9.
- [7] M. Lopez-Benitez and F. Casadevall, "On the Spectrum Occupancy Perception of Cognitive Radio Terminals in Realistic Scenarios", International Workshop on Cognitive Information Processing, Elba, June 2010, pp. 99-104.
- [8] V. Valenta, R. Maršalek, G. Baudoin, M. Villegas, M. Suarez and F. Robert, "Survey on Spectrum Utilisation in Europe: Measurements, Analysis and Observations", in Proc. of ICST Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), Cannes, France, June 2010, pp. 1-5.
- [9] I. F. Akyildiz, W. Y. Lee, M. C. Vuran and S. Mohanty, "NeXt Generation / Dynamic Spectrum Access / Cognitive Radio Wireless Networks: A Survey", Computer Networks, 2006, pp. 2127-2159.
- [10] S. Haykin, "Cognitive Radio: Brain-empowered Wireless Communications", IEEE Journal on Selected Areas in Commun., Vol.23, No. 2, February 2005, pp. 201-220.
- [11] A. L. Drozd, I. P. Kasperovich, C. E. Carroll and A. C. Blackburn, "Computational Electromagnetic Applied to Analyzing the Efficient Utilization of the RF Transmission Hyperspace", In Proc. Of IEEE/ACES Conf. on Wireless Comm. and Applied Computational Electromagnetic, Hawaii, USA, April 2000, pp. 1077-1085.
- [12] J. Mitola and G. Q. Maguire, "Cognitive radios: Making Software Radios More Personal", IEEE Pers. Commun., Vol. 6, No. 4, August 1999, pp. 13-18.
- [13] J. Mitola, "Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio", PhD thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2000.
- [14] M. Matinmikko, M. Mustonen, H. Sarvanko, M. Höyhty, A. Hekkala, A. Mämmelä, M. Katz and M. Kiviranta, "A Motivating Overview of Cognitive Radio: Foundations, Regulatory Issues and Key Concepts", First International Workshop CogART, Aalborg, February 2008, pp. 1-5.
- [15] I. F. Akyildiz, W.-Y. Lee, K. R. Chowdhury: "CRAHNs: Cognitive Radio Ad Hoc Networks", Ad Hoc Networks, Elsevier, Vol. 7, No. 5, July 2009, pp. 810-836.
- [16] D. Čabrić, S. M. Mishra, D. Wilkomm, R. Brodersen and A. Wolisz, "A Cognitive Radio Approach for Usage of Virtual Unlicensed Spectrum", in Proc. of 14th IST Mobile Wireless Communications Summit 2005 Dresden Germany, June 2005, pp. 1-4.
- [17] R. V. Prasad, P. Pawelczak, J. A. Hoffmeyer, H. S. Berger, "Cognitive Functionality in Next Generation Wireless Networks: Standardization Efforts", IEEE Communications Magazine, April 2008, pp. 72-78.
- [18] C. Clancy, J. Hecker, E. Stuntebeck and T. O'Shea, "Applications of Machine Learning to Cognitive Radio Networks", IEEE Wireless Communications, August 2007, pp. 47-52.
- [19] M. Matinmikko, M. Höyhty, M. Mustonen, H. Sarvanko, A. Hekkala, M. Katz, A. Mämmelä, M. Kiviranta and A. Kautio "Channel State Estimation and Spectrum Management for Cognitive Radios, Cognitive Radio: An Intelligent Wireless Communication System", VTT Research report, No. VTT-R-02219-08, March 2008.