Cognitive Radio Technology— A Smarter Approach

Shaika Mukhtar, Mehboob ul Amin

Abstract— **The insatiable desire of man to exploit the radio spectrum is increasing with the introduction newer communication devices. This leads to more spectrum occupation by users which use the spectrum in a limited manner leading to so called spectrum scarcity. This apparent radio scarcity can be overcome by the introduction of a better spectrum utilization strategy. The prime one is dynamic spectrum access which provides a way to utilize the radio spectrum in an efficient manner leading to alleviate spectrum scarcity. This strategy is based on an idea encompassing the opportunistic utilization of the limitedly used spectrum bands. This technique has led to the birth to a new communication technology called as Cognitive Radio Technology which has a dynamic ability to improve spectrum efficiency. It is a smart communication technology where a cognitive radio device senses the environment and communicates using the underutilized spectrum bands. Cognitive radio technology has a potential to satisfy the increasing users. This paper provides a brief description of cognitive radio technology explaining its potential to cope spectrum scarcity. The architecture and cognitive cycle provides an insight view of cognitive radio. Benefits brought by CR can be well understood with the applications given in this paper.**

Index Terms— **Cognitive Radio (CR), Dynamic Spectrum Access (DSA), Federal Communications Commission (FCC), Primary User (PU), Secondary User (SU).**

I. Introduction

We know that the world has witnessed a tremendous increase in the number of wireless services demanding high data rate transmission at low cost. Today, world has become a global village where the people access latest wireless services at any place and at any time. There are two scenarios of the current problem with wireless communication. One scenario is that the number of the wireless users is increasing and the other scenario is that the radio spectrum is limited [1]. So, there is a need to balance these two scenarios by introducing band efficient techniques which can pave a way to boost the wireless communication. One of the solutions is Dynamic Spectrum Access which opens doors to new paradigm called as "Cognitive Radio Technology". The Cognitive Radio is considered as a smarter device which can sense the environment and can get adapted to it. The CR enables the usage of a temporarily unused spectrum, which is referred to as a spectrum hole or a white space [4].

The main precursors for CR research was the seminal work by Mitola [3] and Maguire in 1999 and early spectrum measurement studies conducted as early as in 1995 to quantify the spectrum use, both in the licensed and unlicensed band. In the United States, CR research focused quickly on dynamic spectrum access (DSA) and secondary use of spectrum as the main objectives of the initial research. The most notable project in the spectrum management and policy research was the XG-project funded by DARPA [5]. There have been extensive studies and tremendous researches on cognitive radio in recent years. Some application initiatives, such as the IEEE 802.22 standard on wireless regional area network (WRAN) and the Wireless Innovation Alliance including Google and Microsoft as members, have been developed which advocate to unlock the potential in the so-called "White Spaces" in the television (TV) spectrum. In the standardization domain, three major groups have emerged to work on relevant technologies and architectures: IEEE 802.22 and SCC41 (formally P1900) working groups and ETSI's Reconfigurable Radio Systems Technical Committee on CRs and SDRs. Also, the SDR Forum as an industry group has studied some CR-related issues [8]. Commercially, the most advanced standardization activity is IEEE 802.22 and related research that aims to provide dynamic access to vacant TV spectrum. However, IEEE 802.22 requires a rather limited level of cognition. CR is being intensively investigated and debated by regulatory bodies as the enabling technology for opportunistic access to the so-called TV white spaces (TVWS): large portions of the VHF/UHF TV bands that become available on a geographical basis after the digital switchover. In the United States, the FCC already proposed to allow opportunistic access to TV bands in 2004. Finally, in 2013, FCC has approved Google's plan to operate a database that would allow unlicensed TV broadcast spectrum to be used for wireless broadband and shared among many users. Google is the latest company to complete the FCC's 45-day testing phase. The new database will keep track of the TV broadcast frequencies in use so that wireless broadband devices can take advantage of the White spaces on the spectrum.

The literature has a lot to explore about cognitive radio technology. In [1], FCC has presented a real scenario of the radio spectrum to the world. It is mentioned that due to static spectral allocation strategy, there is "discouraging inefficient" use of allotted spectrum pieces. It described that on one side, there is a huge demand of spectrum, while on other side, there is apparent shortage of spectrum. The scarcity of radio spectrum is due to the due to underutilization of the allotted spectrum bands with spectrum utilization varies from 15% to 85% with wide variance in time and space. Spectrum capacity can also be improved by taking advantage of the geographic distances between radio transmitters. In [3], the author has described that flexible pooling is possible by

Manuscript received Feb, 2016.
Shaika Mukhtar , *Former M.Tech Student , Kurukshetra University*
Mehboob ul Amin, *P.G. Department of Electronics & Instrumentation, Kashmir University.*

ISSN: 2278 – 7798

using Cognitive Radio. Cognitive radio is an extension of software radio employing model-based reasoning about users. This approach helps in expanding the bandwidth available for conventional uses (e.g., police, fire and rescue) and proves useful in extending the spatial coverage of 3G in a novel way. This paper presented the potential contributions of cognitive radio to spectrum pooling. In [4], the author has described cognitive radio as an intelligent wireless communication system that is aware of its environment and uses the methodology of understanding-by-building to learn from the environment and adapt to statistical variations in the input stimuli. This paper described that cognitive radio has to work by ensuring highly reliable communication whenever and wherever needed. Further, efficient utilization of the radio spectrum is the point of concern also. Mitola is credited to have first coined the term "Cognitive Radio" in [3], but it is the Simon Haykin's paper [4] which provides a better concept of Cognitive Radio and is highly cited paper than [3] as per Google Scholar. This paper also tried to explain the behavior of CR by discussing different aspects of CR like radio-scene analysis, notion of interference temperature, channel-state estimation and predictive modeling, etc. In [5], the authors have provided a critical review on the various ongoing efforts towards the use of DSA concept for the frequency management of future wireless communications systems, especially from the Cognitive Radio (CR) perspective. This paper also described various challenges of CR like interference mitigation, QoS guarantee, etc. The CR faces challenges mainly due to the fluctuating nature of the available spectrum band, the need of coexistence and cooperation with the primary devices and the diverse QoS requirements of various applications. In [6], the authors have described the three DSA (Dynamic Spectrum Access) models: interweave, underlay, and overlay. This paper examined the challenges that prevent DSA from major commercial deployment. A new DSA model is proposed, where the licensed users cooperate in DSA to make much more flexible spectrum sharing. To support the future DSA model, the cognitive radio is expected to have several additional entities and capabilities, which would essentially expand the cognitive radio from a physical layer technology to a network technology termed as "Network Radio". The authors have also given its immediate applications like HetNet (heterogeneous networks), which is considered in LTE-A where cells of different sizes coexist. Its long-term application could be the future of wireless communications. In [7], the authors have described that it is not an easy task to make the wireless networks truly cognitive because it requires collaborative effort from various research communities like communication engineering, signal processing, software–hardware joint designing and reconfigurable antenna and radiofrequency designing. This paper provided a systematic overview on CR networking and communications by considering the prime functions of the physical (PHY), medium access control (MAC), and network layers involved in a CR design and also considered their inter-relation. For the PHY layer, this paper addressed signal processing techniques for spectrum sensing, cooperative spectrum sensing, and transceiver design for cognitive spectrum access. This paper also presented a review of the emerging CRNs that are actively developed by various standardization committees and described the challenges posed by these CRNs. In [8], the authors have provided a comprehensive survey on the evolution of CR research covering aspects such as spectrum sensing, measurements and statistical modeling of spectrum usage, physical layer aspects, cognitive learning, adaptation, self-configuration etc. This paper also presented the review on economics of CR networks, CR simulation tools, testbeds and hardware prototypes, CR applications, and CR standardization efforts. Further, the emerging trends on CR research and open research challenges related to the cost-effective and large-scale deployment of CR systems are also described in this paper. In [10], the authors have mentioned that since the formation the IEEE 802.22 Working Group (WG) in 2004, the IEEE 802.22 WG is chartered with the development of a CR-based Wireless Regional Area Network (WRAN) Physical (PHY) and Medium Access Control (MAC) layers for use by unlicensed devices in the spectrum that is currently allocated to the Television (TV) service. Since IEEE 802.22 is required to reuse the inactive TV spectrum, cognitive radio techniques are of primary importance in order to sense and measure the spectrum and detect the presence/absence of incumbent signals. In this paper, a detailed overview of the 802.22 draft specification, its architecture, requirements, applications, and coexistence considerations is provided. The paper described that the future of CR based wireless communication is one of the promising candidates for future wireless communications. Certainly, the 802.22 has a leading and key role for new and innovative research in this promising area. In [11], the authors have provided a review on ten years of research in spectrum sensing and sharing in cognitive radio. Local spectrum sensing is analyzed and mathematically described. Various methods of detection like matched filter detector, energy detector, feature detector etc are described. Since, the performance of spectrum sensing is limited by noise uncertainty, multipath fading, and shadowing, which are the fundamental characteristics of wireless channels, thus an idea of Cooperative sensing is described to overcome such limitations. Others matters like spectrum allocation and spectrum management are also discussed in this paper.

In our paper, an attempt to summarize the various aspects of cognitive radio is done. Here, its basic idea, architecture, basic functional processes are described with benefits and applications described at the end.

II. Overview of Spectrum Scarcity

It has been found that the current spectrum allocation follows static spectrum access technique in which the access to spectrum is given only to incensed users. The current fixed frequency allocation strategy worked well in the past, but with growing proliferation of large number of wireless subscribers and operators, it is proving inefficient in current scenario [5]. As a result, several spectrum regulatory authorities around the world carried out studies on current spectrum scarcity with an aim to optimally manage available radio spectrum. These studies revealed that most of the allotted spectrum is either unused or under-utilized. According to Federal Communications Commission (FCC) [1], spectrum utilization varies from 15% to 85% with wide variance in time and space. This spectrum underutilization

ISSN: 2278 – 7798

leads to formation of spectrum holes which may be defined as a band of frequencies assigned to a primary user, but, at a particular time and specific geographic location, the band is not being utilized by that user. This finding opened doors to a new communication paradigm of sharing the under-utilized radio spectrum through dynamic and opportunistic spectrum access [4].

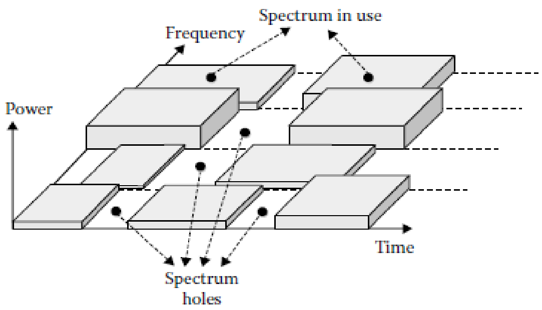

Fig. 1 Spectrum holes concept.

III. Dynamic Spectrum Access

With the increasing demand for additional bandwidth to support entry of a plethora of wireless devices and services, the main challenge to the spectrum policy makers is to solve this apparent spectrum scarcity. Hence, the FCC has commenced work on the concept of unlicensed users "borrowing" spectrum from spectrum licensees. This approach to spectral usage is known as dynamic spectrum access. The DSA techniques are proposed to solve the problem of spectrum scarcity and help to reuse the assigned frequency spectrum and to use the limited spectrum resource as effectively as possible. In fact DSA is considered to be a promising solution to the problem of overcrowded spectrum. The DSA also aims for spectrum sharing to help to overcome the lack of available spectrum for new communications services [3]. The mechanism of DSA requires a flexible approach not only for spectrum sharing but also for technology and service neutrality [6]. It also supports the heterogeneous technologies in the wireless environment. A DSA mechanism may be agile or flexible. This idea makes spectrum access more flexible by allowing the unlicensed users to access the radio spectrum under certain restrictions. DARPAs approach on Dynamic Spectrum Access network, the so-called NeXt Generation (xG) program aims to implement the policy based intelligent radios known as cognitive radios. Thus, the key enabling technology of dynamic spectrum access techniques is cognitive radio (CR) technology, which provides the capability to share the wireless channel with licensed users in an opportunistic manner [9].

IV. Cognitive Radio Technology

Cognitive radio is an exciting promising technology which not only has the potential of dealing with the inflexible prerequisites but also the scarcity of the radio spectrum usage. Such an innovative and transforming technology presents an exemplar change in the design of wireless communication systems. It is currently experiencing rapid growth due to which various Wireless device manufacturers (e.g., Motorola, Eriksson, and Nokia), telecommunication operators (e.g., BT, France Telecom), and chip makers (e.g., Intel) are all beginning to invest in this new technology, especially with respect to research and development [8][13].

There are two types of spectrum users:

A. *Primary users:* These wireless devices are the primary license holders of the spectrum band of interest. In general, they have priority access to the spectrum and are subject to certain quality-of-service (QoS) constraints that must be guaranteed.

B. *Secondary users:* These users may access the spectrum, which is licensed to the primary users. They are the secondary users of the wireless spectrum and have lower priority.

These cognitive users employ their "cognitive" abilities to communicate while ensuring the communication of primary users is kept at an acceptable level. Cognitive radio offers a novel solution to overcome the underutilization problem by allowing an opportunistic usage of the spectrum resources. Here, a SU can access spectral resources of a PU when the PU is not using them. However the SU has to vacate the frequency band as soon as the PU becomes active so that negligible interference is caused to the PU [5].

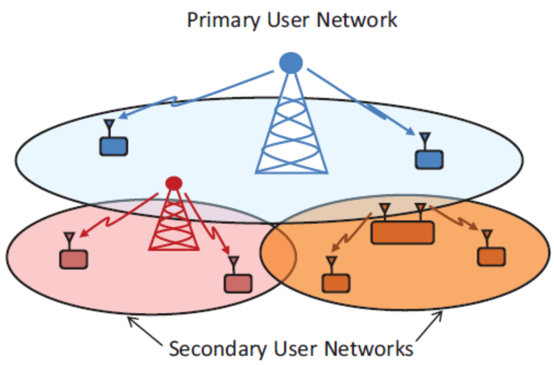

Fig.2 Coexistence of multiple primary and secondary user networks

The observations published by FCC have described two types of spectrum holes: temporal spectrum holes and spatial spectrum holes. A temporal SH appears when there is no PU transmission during a time period and the SUs can use the spectrum for transmission. A spatial SH appears when the PU transmission is within an area and the SUs can use the spectrum outside that area. By sensing and adapting to the environment, a CR is able to fill in spectrum holes and serve its users without causing harmful interference to the licensed user. Thus, CR is designed to identify and scavenge the spectrum holes in the licensed spectrum bands. The cognitive radio has unique cognitive capability and reconfigurability [4], [5].Cognitive capability refers to the ability to sense and gather information from the surrounding environment. With this capability, secondary users can identify the best available spectrum. Reconfigurability refers to the ability to rapidly adapt the operational parameters according to the sensed information in order to achieve the optimal performance. By exploiting the spectrum in an opportunistic fashion, cognitive radio enables secondary users to sense which portion of the spectrum are available, select the best available channel, coordinate spectrum access with other users, and vacate the channel when a primary user reclaims the spectrum usage right .

ISSN: 2278 – 7798

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. With recent developments in CR technology, it is now possible for these systems to simultaneously respect the rights of incumbent license holders while providing additional flexibility and access to spectrum [8]. A cognitive radio has three important characteristics: awareness, cognition, and adaptability. Awareness is the ability of the radio to measure, sense, and be aware of its environment and internal states [9]. A radio may exhibit different levels of awareness such as spectrum awareness, location awareness, user awareness, and network awareness, etc. Cognition is the ability to process information, learn about the environment, and make decisions about its operating behavior to achieve predefined objectives. Adaptability is the capability of adjusting operating parameters for the transmission on the fly without any modifications on the hardware components. This capability enables the cognitive radio to adapt easily to the dynamic radio environment. There are several reconfigurable parameters: frequency, transmit power, waveforms, antenna configuration, communication technology, and protocol.

V. Cognitive Radio Architecture

The typical cognitive radio architecture consists of three sub-systems:

- Digital transceiver ,
- Channel monitoring and spectrum sensing module and
- Communication management and control unit

The digital transceiver further consists of RF front end and baseband processing unit as shown below

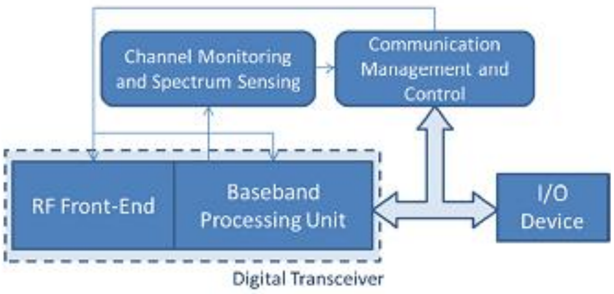

Fig 3 : Cognitive Radio Physical Architecture

The RF front-end module corresponds to the hardware part of CR whose function is the reception, down conversion, amplification, mixing, filtering etc. The RF front-end consists of the receiver and the transmitter analog functions [4]. The receiver and transmitter generally consist of frequency up converters and down converters, filters, and amplifiers. Sophisticated radios will choose filters and frequency conversions that minimize spurious signals, images, and interference within the frequency range over which the radio must work. The front-end design will also maximize the dynamic range of signals that the receiver can process, through automatic gain control (AGC).The baseband processing unit is implemented in software and is responsible for all the necessary digital processing of the signal like modulation and coding [5]. The channel monitoring and spectrum sensing module is capable of spectrum sensing and sending information to communication management sub-system so that the CR can adjust its operation parameters. The communication management and control subsystem manages all CR operations namely switching mode decisions [14].

VI. COGNITIVE CYCLE

The CR exploits the dynamic spectrum environment requiring information about the changing conditions of spectrum environment. The requisite steps for the functioning of CR lead to the cognitive cycle consisting of various spectrum management functions [4]. The CR network performs the following four functionalities; Spectrum Sensing, Spectrum Decision, Spectrum Sharing and Spectrum Mobility.

A. *Spectrum sensing:* A Cognitive Radio based device is not allowed to allocate spectrum wherever it desires but only on those portions of the spectrum where it does not interfere significantly with the primary. This is a very important requirement to ensure coexistence with the primary, and to fulfill the spectrum sharing requirements. The continuous sensing of the wireless environment is mandatory for the secondary devices to fulfill such functions. Thus, a CR user can be allocated to only an unused portion of the spectrum. Therefore, a CR user should monitor the available spectrum bands and then detect the spectrum holes. Spectrum sensing is a basic and crucial functionality in CR.

B. *Spectrum decision*: The availability of certain spectrum band may be known based on the sensing information. The allocation of the spectrum band does not depend only on the availability but also takes into account the regulatory policies. The decision to allocate the spectrum is taken based on these facts .Once the available spectrums are identified, it is essential that the CR users select the most appropriate band according to their QoS requirements. It is important to characterize the spectrum band in terms of both the radio environment and the statistical behaviors of the PUs.

C. *Spectrum sharing*: Since there may be multiple CR users trying to access the spectrum, their transmissions should be coordinated to prevent collisions in overlapping portions of the spectrum. Thus, Spectrum sharing provides the capability to share the spectrum resource opportunistically with multiple CR users, which includes resource allocation to avoid interference caused to the primary network. For this reason, game theoretical approaches have also been used to analyze the behavior of selfish CR users.

D. *Spectrum mobility*: In fact the Cognitive Radio devices are considered as the visitors to the spectrum. The secondary device may use any band of the spectrum, but a PU is detected in the specific portion of the spectrum in use, CR users should vacate the spectrum immediately and continue their communications in another vacant portion of the

ISSN: 2278 – 7798

spectrum. For this reason, either a new spectrum must be chosen or the affected links may be circumvented entirely. Thus, spectrum mobility necessitates a spectrum handoff scheme to detect the link failure and to switch the current transmission to a new route or a new spectrum band with minimum quality degradation so as to have seamless communication during transition to better spectrum [14].

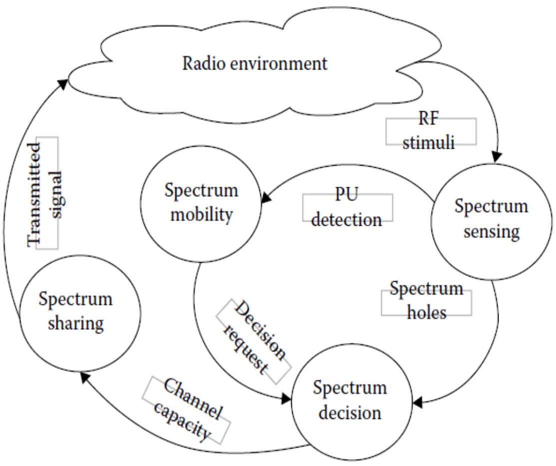

Fig 4. Cognitive Cycle

VII. Cognitive Radio Challenges

The Cognitive Radio technology offers many potential benefits such as improving spectrum utilization, introducing innovative resource management schemes, generating new revenues, facilitating optimized services and making high bandwidth available to the users [11]. The CR impose challenges mainly due to the fluctuating nature of the available spectrum band, the need of coexistence and cooperation with the primary devices and the diverse QoS requirements of various applications [12]. The critical design challenges of CR are the following:

- *Interference Minimization:* The CR network aims coexistence of PUs and SUs, but the requirement is to have minimal possible interference to the primary devices This is considered to be a critical design challenge. Appropriate schemes must be investigated to find the suitable approaches.
- *QoS Guarantee*. The CR device uses the spectrum in an opportunistic manner and therefore, the quantity of used spectrum fluctuates over the spectrum bands. This makes difficult to guarantee the specific Quality of Service (QoS) requirement of users. This is a challenging task and suitable schemes must be investigated for this.
- *Seamless Communications*: The communication in the CR network may be disrupted due to spectrum mobility and also due to lack of spectrum availability. Therefore, providing seamless communication becomes challenging in the Cognitive Radio environment.

VIII. Benefits of Cognitive Radio

As we know that cognitive radio is a smart device which can opportunistically use white space in licensed bands without causing interference [16]. There are several benefits of cognitive radio technology.

- *Improved Communication Structure:* CR creates an improved communication structure by allowing different devices supporting different technologies to communicate with each other. This will be helpful in disasters where a cognitive radio with support for military standards and other public safety standards would solve this problem.
- *Ease of up gradation:* With time, new revisions of standards are released. Cognitive radio allows an upgrade of the existing equipment to this new release without replacing the hardware.
- *Introduction of new services:* New services could be enabled more easily by cognitive radio, as it can adjust its parameters according to the requirements of the new service. It does not have limitations set by existing standards.
- *Improved reliability:* A cognitive radio always tries to minimize interference to other networks by changing its frequency if other signals are present. This feature automatically makes a cognitive radio more resilient to jamming.

IX. Applications of Cognitive radio

An interesting aspect we observe with respect to CR is that it fits many fields of scientific and engineering endeavors. For example, it stimulates signal processing techniques with respect to detection and sensing; it looks like a fertile area of application for artificial intelligence (AI); it provides new creative opportunities for systems specialists. Cognitive radio presents the possibility of numerous revolutionary applications apart from dynamic spectrum access. For example, cognitive radio may facilitate location services, seamless mobility, optimum performance, and coexistence of heterogeneous wireless systems. Cognitive radio may provide location services by helping the user locate services like restaurants, car rental, train, flights, etc., when he travels in a new country [13]. Cognitive radio may facilitate seamless mobility by automatically detecting and inter operating with different networks like WLAN, wireless metropolitan area network (WMAN), Bluetooth, etc. Cognitive radio may be useful in obtaining optimum performance by optimizing spectrum usage, data rates, service cost, battery power minimization, etc., or a mix of such objective functions. Cognitive radio can provide solutions to reduce the interference among the coexisting heterogeneous wireless systems and improve their performance [16]. Even 3GPP is considering cognitive radio in its future releases. The immediate applications of cognitive radio concept is HetNet (heterogeneous networks), which is considered in LTE-A where cells of different sizes coexist. Its long-term application could be the future of wireless communications.

Conclusion

The current strategy of fixed spectrum assignment embraces the concept of partitioning the spectrum into numerous spectrum pieces of different ranges. This

ISSN: 2278 – 7798

assignment has led to so called "spectrum scarcity". Cognitive radio technology has a potential to alleviate this spectrum scarcity to satisfy the increasing users, but still there are some aspects of Cognitive Radio which need a proper consideration in order to practically implement it. Interference mitigation and capacity enhancement in cognitive radio network are some of the requirements for better communication in cognitive radio network. The need is to reduce the interference among the users to have better spectrum sensing. So, radical approaches are needed which can help to implement the cognitive radio technology in real sense.

REFERENCES

[1] FCC, Spectrum Policy Task Force, ET Docket 02-135, Nov. 2002.

[2] FCC , Spectrum Policy Task Force Report, ET Docket No. 04–186, Sep. 2010

[3] Mitola J. III ,"Cognitive Radio for Flexible Mobile Multimedia Communications", IEEE International Workshop on Mobile Multimedia Communications, pp.3-10, Nov. 1999.

[4] Haykin S., "Cognitive Radio: Brain-Empowered Wireless Communications", IEEE Journal on Selected Areas in Communications, Vol. 23, Issue 2, pp. 201–220, Feb. 2005.

[5] Kumar S. , Sahay J. , Mishra G.K. , Kumar S. , "Cognitive Radio Concept and Challenges in Dynamic Spectrum Access for Future Generation Wireless Communication Systems", Springer, Journal on Wireless Personal Communication, Vol.59, Issue 3, pp 525-535, 2011

[6] Song M. , Xin C. , Zhao Y. , Cheng X. , "Dynamic Spectrum Access: From Cognitive Radio to Network Radio", IEEE Wireless Communications,Vol.19, Issue 1, February 2012.

[7] Liang Y.C. , Chen K.C. , Li G.Y. , Mahonen P. , "Cognitive radio Networking and Communications: An Overview", IEEE Transactions on Vehicular Technology, Vol.60, No.7, September 2011.

[8] Hossain E. , Niyato D., Kim D.I. , "Evolution and Future Trends of Research in Cognitive Radio: A Contemporary Survey" ,Wiley Online Library, Journal on Wireless Communications and Mobile Computing, Vol.15, Issue 11, pp.1530-1564, 2013

[9] Ian F. Akyildiz, et al., "NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey", Elsevier, Computer Networks 50 (2006) 2127–2159

[10] Cordeiro C. , Challapali K. , Dagnachew B. , Sai S.N., "IEEE 802.22: An Introduction to the First Wireless Standard based on Cognitive Radios" ,IEEE, Proceedings of the IEEE International Conference on Dynamic Spectrum Access Networks, Journal of Communications, Vol. 1, No. 1, April 2006

[11] Lu L. , Zhou X. , Onunkwo U. , Li G.Y. ,"Ten years of research in Spectrum Sensing and Sharing in Cognitive Radio," EURASIP Journal on Wireless Communications and Networking 2012, 2012:28

[12] Mohamed Ghozzi et al.,"Cognitive radio: methods for the detection of free bands", Elsevier, C. R. Physique 7 (2006) 794–804

[13] Gianmarco Baldini et al., "The Evolution of Cognitive Radio Technology in Europe : Regulatory and Standardisation Aspects" ,Elsevier, Telecommunications Policy 37 (2013) 96–107

[14] Joanna Wallace et al.,"Cognitive Radio Technology: System Evolution", IEEE, 4th Edition of International Conference on Wireless Networks and Embedded Systems ,2015

[15] Alexander M. Wyglinski, "Cognitive Radio Communication and Networks", Elsevier Publication

[16] Guolin Sun et al., "Benefits brought by Cognitive Radio for the Next Generation Cellular Networks: A perspective from industry" , Elsevier, Physical Communications , pp2-9,2012

ISSN: 2278 – 7798