ISSN 2320 - 2602

International Journal of Advances in Computer Science and Technology (IJACST), Vol. 4 No.1, Pages : 32 –42 (2015)
Special Issue of ICCSIE 2015 - Held during January 16, 2015, Bangalore, India
http://warse.org/pdfs/2014/iccsie2015sp05.pdf

Empirical Study on Cognitive Radios and Cognitive Networks

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ABSTRACT

KEYWORDS: Software defined radio, Cognitive radio, Cognitive cycle, Cognitive networks, Cross layer design, Performance metrics.

I. INTRODUCTION

WIRELESS communication created a revolution in our lives. New wireless devices are capable of offering higher data rates and innovative services. Licensed and unlicensed spectrum is available for different wireless services. But with the exponential increase in wireless devices and their usage, the unlicensed spectrum is becoming scarce [1] [2]. Licensed spectrum is used for specific service while the unlicensed spectrum (Industrial, Scientific and Medical (ISM) radio bands) are freely available for wireless services and research purposes. Currently static spectrum allocation policy is in practice due to which bandwidth in unlicensed bands is becoming scarce and for licensed bands it is either underutilized or unoccupied [3] [4]. Licensed spectrum specifically TV spectrum and cellular spectrum are underutilized [3]. According Federal **c**ommunications **c**ommission (FCC) 2002, the licensed bands are underutilized and the ISM bands are over utilized [5]. This report also stated that licensed bands average utilization is 15-85% [5]. The unutilized portion of licensed spectrum is known as white space. White space could be defined by time, frequency and maximum transmission power at a specific location [2]. This spectrum inefficient utilization occurs due to static spectrum allocation policy adopted by the governments worldwide. Solution to this inefficient spectrum utilization is dynamic spectrum access and allocation.

The above mentioned statistics from FCC report show ineffectual utilization of spectrum which encouraged researchers to develop new spectrum sharing methodologies. The idea of cognitive radio provides a solution by which efficient spectrum utilization is possible by applying the optimistic spectrum sharing techniques [6]. The concept of cognitive radio was first purposed by J. Mittola in 1999 [7]. The cognitive radio is a spectrum agile system which has the ability to sense the communication environment dynamically and it can intelligently adapt the communication parameters (carrier frequency, bandwidth, power, coding schemes, modulation scheme etc.) [8]. Cognitive user should be capable of sensing the environment for the estimation of available resources and application requirements and could adopt their performance parameters according to user request and available resources [9]. Secondary (cognitive) user can utilize the licensed spectrum (available white spaces) without affecting the priority utilization of the spectrum by primary user. In this way, it maximizes the efficient licensed spectrum utilization. The hardware challenges of cognitive radio are catered by techniques like **S**oftware define radio (SDR) [10] and **A**pplication specific integrated chips (ASIC) [11]. **Considering** the transmission and reception parameters, **c**ognitive radios can be divided in to two categories.

Full cognitive radio

Spectrum sensing cognitive radio.

A. Full Cognitive Radio

The type of cognitive radio in which almost every parameter of wireless node or network is considered [10].

B. Spectrum-Sensing Cognitive Radio

In case of spectrum sensing cognitive radio only spectrum of radio frequency is considered [12].

In United States, FCC allowed the dynamic access of the UHF TV bands by the cognitive radio devices [13]. The bands below 3.5 GHz due to lower propagation loss are ideal candidates for cognitive radio. Typical candidate bands below 3.5 GHz are UHF TV band, cellular bands and fixed wireless access bands [13].

The rest of the paper is organized as; section II describes the spectrum scarcity and spectrum sharing. Software defined radio is explained in section III. Section IV describes the cognitive radio and cognitive cycle. Section V explains cognitive radio networks. In section VI few examples of cognitive radio architectures are given. In section VII the concept of cross layer design is discussed. In section VIII node and network level performance metrics are explained. Finally **s**ection IX concludes the paper.

II. SPECTRUM SCARCITY AND SPECTRUM UTILIZATION

FCC reported that the spectrum utilization of the bands below 3 GHz is only 5.2% in United States at any given location and time [14]. The fixed static spectrum allocation policy is the main reason behind this varying licensed band inefficient spectrum underutilization. The demand of the radio spectrum is increasing dramatically specially for the **m**obile **r**adio **c**ommunications. This policy is also responsible for the inefficient spectrum utilization and spectrum scarcity problem. In ISM bands congestion is increasing rapidly as it is overcrowded due to WLAN, Bluetooth, cordless phones, microwave ovens and other devices. In this situation of inefficient RF spectrum utilization and spectrum scarcity, there is a need of new system to efficiently utilize available spectrum resources in a dynamic way to fulfill growing bandwidth demands. This new system should be able to sense the spectrum, detect spectrum holes and utilize these spectrum holes and hence improving overall spectrum utilization.

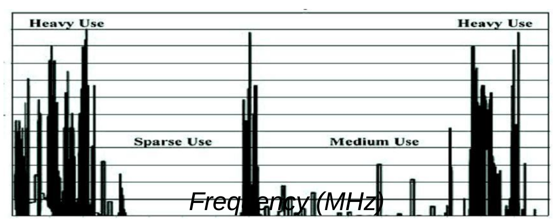

Fig. 1. Spectrum Utilization [15]

Fig. 1 shows the distribution of signal strength on the wireless spectrum. According to Fig. 1 significant amount of spectrum remains underutilized due to fixed spectrum access policies.

III. SOFTWARE DEFINED RADIO

Software define radio (SDR) is a type of communication transceiver in which all the typical functions of communication system like mixing, amplification, modulation/demodulation, detection are implemented through software. This software is then implemented on reconfigurable hardware which could be used for more than one communication systems. All we need is swapping the software on reconfigurable hardware depending upon type of communication system [16].

Software radio was first time designed and implemented by Garland Texas division of E-Systems in 1984 [17]. In 1988 Helmuth Lang and Peter Hoeher designed first transceivers on the basis of software radio at German aerospace research establishment (DFVLR). This transceiver was designed for a satellite modem [18]. In 1991 Joseph Mitola III coined the term software define radio for a communication system that includes 80% software and 20% hardware components instead of conventional 80% hardware and 20% software approach [19].

SDR systems are cheaper and easy to design due to re-programmability and software based implementation [20]. The new and different protocols could be implemented in SDR. It supports a broad range of frequencies, air interfaces and application software [21]. SDRs are multi-functional and provide global mobility, compactness and consume less power [21]. As the radio functions are implemented with the help of software in SDR, so these functions could be easily upgraded and run time reconfiguration is possible. The **s**oftware defined radio based networks have the layered architecture [22]. Speak easy, JTRS, Joint **c**ombat **i**nformation **t**erminal (JCIT), CHARIOT, Spectrum Ware and GNU Radio are the few examples of SDR based projects [23].

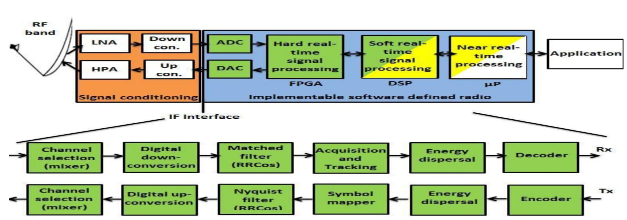

Fig. 2. Implementable SDR Mapped on Transceiver Functions [24]

Fig. 2 shows implementable software defined radio with all the necessary components. Fig.2 also shows necessary signal processing that is applied to transmit and receive the desired signal using 80% software instead of hardware [19].

IV. Cognitive Radios

Cognitive radios are self-aware and intelligent devices which 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 [12]. 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 **e**ngine (CE).

A. Cognitive Cycle

The **c**ognitive **e**ngine works according to the cognitive cycle [7] [12]. The cognitive cycle consists of various steps as shown in fig.3. This cycle includes analyzing the RF stimuli from outside environment and sensing spectrum holes. It also includes functions like transmission power control and spectrum management after sensing the white spaces to ensure interference free opportunistic spectrum access.

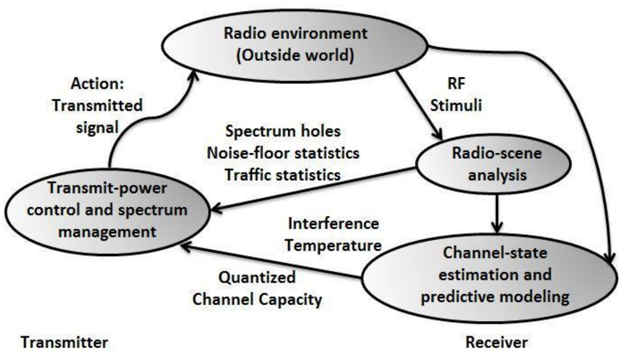

Fig. 3. Cognitive Radio Cycles [7] [12]

The cognitive engine performs the tasks of sensing, analysis, learning, decision making and reconfiguration [25]. Cognitive radio networks consist on two types of users, primary (licensed) and secondary (unlicensed or cognitive) users. Licensed users have higher priority for the usage of the licensed spectrum [26]. 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 [26] [27].

On the basis of incoming RF stimuli the spectrum utilization could be classified in to three broader categories black spaces, grey spaces and white spaces. *Black spaces* are potion of licensed spectrum being used by primary users and is occupied by high power signals. *Grey spaces* are temporary occupied by low power interfaces and *white spaces* are free from RF interferences and are purely unutilized portion of licensed spectrum. White and grey spaces are candidates for the communication of secondary user in licensed bands [12].

As cognitive radio utilize unused licensed spectrum, thus reducing spectrum scarcity and underutilization problem of the licensed spectrum bands.

The important functions of a CR include [28].

1) Spectrum Sensing

Spectrum sensing **means** to sense the unutilized spectrum bands. Detection of spectrum holes is one of the basic functions of cognitive radio. Spectrum sensing techniques could be braodly catagorized as

a) Trasmitter Detection

A way of spectrum sensing in which presence of **primary transmitter** signal is sensed. It could be achived by the techniques like energy detection, cyclostationary feature detection and matched filter detection.

b) Cooperative Detection

In this method information from various cognitive users is used to sense primery user presence.

c) Interference Based Detection

In this method primary user is detected on the basis of RF interference.

*2) Spectrum **Management***

It is the process of capturing best available spectrum considering user and QoS **requirements**. Spectrum management is an important function of cognitive radio as it decides the best available spectrum opportunity for secondary users. Spectrum management function could be further classified in to *spectrum analysis* and *spectrum detection.*

3) Spectrum Mobility

Spectrum mobility refers to the transition of cognitive user from one frequency to another. This transition is possible due to detection of some other best spectrum opportunity or due to primary user detection on the same spectrum. As cognitive radio works on the basis of dynamic spectrum access thus maintains seemless transitions.

4) Spectrum Sharing

Spectrum sharing refers to spectrum sheduling. It enables CR users to efficiently utilze and share used licensed spectrum. Specrtum sharing is one of the major challenges of open spectrum access.

V. COGNITIVE RADIO NETWORK

A. Cognitive Radio Network Paradigms

Primary concern of cognitive radio is to ensure that cognitive user will not interfere with the licensed user while communicating in licensed spectrum. Based on available network information and other regulations there are different approaches by which secondary user access spectrum without interfering with primary user. These approaches include *under lay, overlay and interweave paradigm* [29] [30].

1) Underlay Paradigm

In this approach, secondary users simultaneously transmit with the primary users by maintaining endurable interference. This could be achieved by maintaining interference at primary receiver by secondary users below certain threshold [29] [30] [31]. Underlay approach uses interference temperature model for measuring interference level at primary receiver caused by secondary users and uses measured data to minimize the interference caused by secondary user [29]. The interference problem caused by secondary users could also be solved by the use of multiple antennas by which secondary user transmission could be guided away from primary receiver. Another approach for reducing interference is the use of wide bandwidth on which secondary transmission could spread while dispreading signals at secondary receiver; this technique is also basis for spread spectrum and Ultra-**w**ide-**b**and (UWB) communication [30]. The underlay paradigm could also be use in unlicensed bands for providing various class of service for different users [30].

2) Overlay Paradigm

In overlay technique interference is mitigated and in some cases completely cancelled as secondary user uses codebook information and messages that primary user sends. In this way primary users assist secondary users for simultaneous transmission by using portion of their transmitting power. As the secondary user knows both message and codebook to decode the message it can apply various coding schemes so that data rate of both secondary and primary users could be improved using this information. Famous coding schemes for this purpose include: Superposition **c**oding, Gel'fand **p**insker (GP), Dirty-**p**aper **c**oding (DPC), Rate-splitting etc. Among these Rate-splitting is best known coding scheme till now [29].

3) Interweaver Paradigm

Interweaver paradigm uses opportunistic spectrum access method that was primary idea of cognitive radio [7].

It is based on the fact of spectrum underutilization which indicated that there are temporary space-time frequency holes that could be utilized by cognitive users. Existence of these holes depends on time and geographical location. For efficient and interference free communication cognitive user requires activity based information of licensed and unlicensed users [29]. In more general perspective interweaver cognitive radios are intelligent systems that sense the

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unused spectrum opportunistically, utilizing it for communication and leaving the spectrum when primary user is detected thus avoiding considerable interference [29].

To summarize, both underlay and overlay techniques allow simultaneous transmission of primary and secondary users while interweaver paradigm avoids simultaneous transmission and uses opportunistic spectrum access method. Moreover different paradigms require different information; like underlay paradigm require interference information at primary receiver, overlay paradigm requires codebook and message information and interweaver paradigm requires licensed and unlicensed user's activity information for efficient detection and utilization of spectrum holes.

Cognitive Radio Network Paradigms
Under lay Paradigm: Simultaneous primary and secondary transmission maintaining endurable interference. Uses interference temperature model to measure interference at primary receiver.
Overlay Paradigm: Simultaneous primary and secondary transmission. Interference is mitigated or avoided using codebook information and message exchange between primary and secondary users.
Interweave Paradigm: Uses opportunistic spectrum access technique. Secondary user utilizes available spectrum holes thus avoiding simultaneous transmission.

Table. 1. Summary of Cognitive Radio Network Paradigms

B. Cognitive Radio Network Frameworks

The **U**nified theory of cognition (UTC) [32] is the key component behind the designing of the cognitive radio architectures. In cognitive architectures the intelligent entities react with the inputs [33]. UTC shows how intelligent cognitive entities react in response to environment input to achieve specific goal [33]. Fig. 4 shows classification of cognitive radio frameworks.

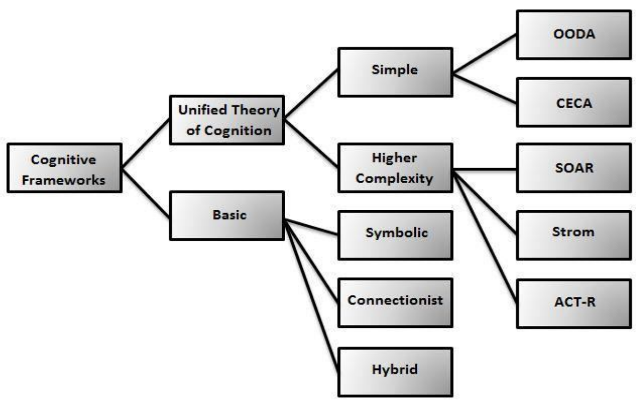

Fig. 4. Classification of Cognitive Frameworks [33]

Here only frameworks based on unified theory of cognition will be disscussed.

1) Simple Model

Classification of cognitive frameworks described in Fig.4 shows simple model of UTC includes Observe-**o**rient-**d**ecide-**a**ct (OODA) loop and Critique-**e**xplore-**c**ompare-**a**dapt (CECA) loop. Both of these are further explained in following sections.

a) Observer-Orient-Decide-Act (OODA) Loop

OODA is a concept of decision making proposed by John Boyd. It was basically designed for decision making in fighter pilot combat on the basis of observed environment [33] [34]. The use of OODA loop for cognitive radio decision making process was first purposed by Mitola and Maguire in 1999 [35]. In cognitive prospective the dubbed version of OODA loop *observes* the radio environment and learns from previous mistakes, *orient* the adaptation process, *decide* to perform a specific action and *acts* at the end to perform decided task in particular radio environment [36]. All these steps are repeated in a loop. Mitola cognitive radio architecture was also based on OODA loop [33].

b) Critique-Explore-Compare-Adapt (CECA) Loop

CECA is a simple but wildly applicable concept that studies decision making process in the context of command and control [37]. With the growth of cognitive application from single radio to radio network and large scale network there will be need of multi-systems components to handle such networks [38]. It indicates for future cognitive applications the strictly reactive approach may not be feasible and proactive approach like CECA could be used to optimize performance [33]. The CECA loop is started with the creation of conceptual model [37]. The conceptual model is the result of initial plan of action and maintains the goals of operation and information of how these goals could be achieved [37]. The CECA concept claims that OODA loop inadequately describes the decision making process of proactive goal-oriented command [37].

2) High Complexity Model

High complexity models based on UTC philosophy [39] are SOAR, Storm and ACT-R. Details of the models are provided in the following sections.

a) SOAR

SOAR is a general cognitive architecture that was developed in 1983, since then SOAR had been used in various fields. SOAR is used to develop systems that possess intelligent behavior [33]. SOAR is one of the first architectures developed in cognitive and artificial science communities [35].

Main components of SOAR include Problem **s**paces, Long-term **p**roduction **m**emory, Short-term **m**emory and Preference **m**emory. Problem spaces are set of states and operators that manipulate these states; **l**ong-term production memory contains rules for conditions and actions; short-term memory has attributes and values of context stack and preference memory contains preferences for particular context memory objects [35].

Execution cycle of SOAR consists of two phase process elaboration and decision. In *elaboration* phase all the matching productions are executed while in *decision* phase tasks like preferences analysis, loading next problem space, goal or operator in context stack are performed [35]. Open source **c**ognitive **r**adio is designed on the basis of SOAR [33].

b) Storm

Storm is an extension of SOAR cognitive radio architecture. It is a biologically inspired architecture that is developed by adopting knowledge of psychology and brain based science to original SOAR architecture [40]. Due to complexity; it is not implemented on any practical platform [40].

c) ACT-R Model

ACT-R was developed by Carnegie Mellon University by studying the human psychology and the way human cognition works [41]. ACT-R architecture consists of processing modules and buffers associated with them. Different modules included are sensory information, beliefs, goals, actions and declarative knowledge. Buffers associated serve as short term memory and contain information in the form called "declarative chunks". Long term memory in ACT-R model consists of production rules containing conditions and actions [35].

ACT-R could also be utilized to model cognitive radio tasks. It is modeled in a programming language that is used to represent tasks. Model developed using ACT-R programming language is tested against tasks performed by real people and comparing these with tradition cognitive phycology metrics. These metrics include time to perform the task and accuracy of performance. Both of these metrics could also be used for performance measurement of cognitive radios [33].

Cognitive Radio Architecture	Architecture Type
OODA: Loop for molding situations requiring adaptation to changing environment.	Simple
CECA: Extension to OODA loop used to model situations in broader context.	Simple
SOAR: Used to develop systems that possess intelligent behavior. One of the first architectures developed in cognitive and artificial science communities.	Complex
Storm: Extension to SOAR. It is biologically inspired architecture developed by adopting knowledge of psychology and brain based science to original SOAR architecture.	Complex
ACT-R: Modeled in a programming language that is used to represent tasks. The developed models are tested against tasks performed by real people and comparing these with tradition cognitive phycology metrics.	Complex

Table. 2. Summary of Cognitive Radio Architectures

VI. Examples of Cognitive Radio Architecture

A. Mitola Cognitive Radio Architecture

This architecture was proposed in 2000 by Joe Mitola in his PhD dissertation. Mitola cognitive radio architecture is basis on the concept of OODA loop. For cognitive radio the observe state of OODA loop senses the spectrum, orient state prioritizes the observations and decisions and finally action is perform to achieve the goal [33].

B. Case Based Reasoning Cognitive Engine (CBR)

Case **b**ased **r**easoning (CBR) is based on reinforcement learning principle [42] [43]. Solution making in CBR depends on past experience as past experience is formulated as knowledge [44]. Performance of CBR is poor for new situations as compared to familiar scenarios; this problem could be solved using creative solutions such as evolutionary search algorithm [44].

CBR engine uses a modular approach with interface between each module so that each module is flexible enough to be individually modified without changing entire engine [33]. Basic modules include **c**ase-based **r**easoner, **s**pectrum **m**anager, **c**onstraint and **p**olicy **e**ngine, **m**ulti-objective optimizer and databases like map of radio environment [45].

IEEE 802.22 is based on CBR cognitive engine that is first cognitive wireless standard. The 802.22 was proposed in November 2004 [46]. It was the first cognitive radios based world wide effort to define a novel wireless air interface for the PHY and MAC layers [46]. This standard was developed by the 802.22 working group [47]. The basic task of the working group was the development of PHY and MAC layers for CR based Wireless **r**egional **a**rea **n**etwork (WRAN) [47]. Major functionalities include sensing and detection of the incumbent signal, so that interference due to incumbent users can be avoided and flexible spectrum band can be obtained by frequency reuse [47]. This standard enables the unlicensed devices to operate in the **t**elevision (TV) band using white spaces [47].

C. Public Safety Cognitive Radio

Cognitive radio technology is designed keeping in mind public safety considerations [44]. Like CBR this architecture also uses modular approach. In this architecture functionality of CR node is divided into three domains; policy domain, radio domain and user domain [33].

Environment modeling is included in modules that involve collection of information and domains recognition. Information obtained through environmental modeling is then forwarded to learning core. In public safety cognitive radio generated solutions are further optimized using adaptive genetic algorithm [33].

D. Open Source Cognitive Radio (OSCR)

OSCR project was designed for the integration of cognitive engine with multiple software communication architecture (SCA) [33]. The OSCR consist of two main components multiplexer and SCA resource in each radio. Multiplexer acts as control point for cognitive engine while SCA resource acts as translator between OSCR API and radio's native API [48].

OSCR enables the connection of multiple radios with single cognitive engine with the help of application programming interface (API). OSCR was designed with the help of SOAR approach. The goal of OSCR was to maximize the capacity of noisy channel [48].

E. DARPA Next Generation (XG) Program

Defense **a**dvanced **r**esearch **p**rogram **a**gency (DARPA) XG radio program focuses on the development of policy driven radio based on use of ontological reasoning on SDR platform [33]. Directions are provided to SDR platform using two separate ontological reasoning engines for policy and waveform [33].

This program is designed to make a strategy for unused spectrum. The main task is to avoid the interference of hidden users. It uses **D**ynamic spectrum access capability (DSA) which provides information of unused channels in the available spectrum. The DARPA XG creates and modifies policies using Web **o**ntology **l**anguage (OWL) [33].

VII. CROSS LAYER DESIGN

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 [49]. CR senses the environment using information from **p**hysical and MAC layer. Present protocols designed for the **p**hysical and M**AC** 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 **p**hysical layer. It also helps the M**AC** layer in assigning the resources to radio nodes. The decisions will be done on the basis of information provided by the Physical layer [47].

Available reconfigurable parameters of the SDR can be determined through cognitive process. These writeable parameters are known as *knobs*. Knobs allow CR to change setting for **p**hysical and MAC layer according to requirements [47].

A. Physical Layer

The main task of the **p**hysical layer in CR networks is to sense the channel to check the presence of primary user and to find the spectrum hole. Various detection schemes and sensors enable physical layer to detect primary user. Physical layer also measures the amount of interference during the channel occupancy by the secondary user. Finally signal is shaped at transmitter to avoid intolerable interference to meet the QoS requirements. Occupancy of channel by primary user is represented by T_{on} (occupied) and T_{off} (unoccupied) [49].

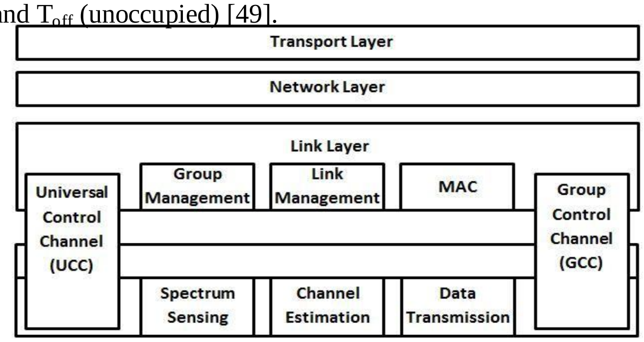

Fig. 5. General OSI Stack for the Cognitive Radio Based Networks [50]

In fig. 5 general OSI stack is shown. It also represents the functions of **p**hysical and MAC layer and relationship between both for cognitive radio network. According to fig.5 **p**hysical layer performs tasks like **s**pectrum **s**ensing, **c**hannel **e**stimation and **d**ata **t**ransmission. While **l**ink layer controls **g**roup **m**anagement, **l**ink **m**anagement and MAC.

B. MAC Layer

MAC layer uses the T_{on} and T_{off} information for the decision about switching to a new channel and distribution of information among other secondary users. MAC layer uses T_{on} and T_{off} information to determine the guaranteed rate that a particular unoccupied channel could provide. It also manages the admission control and scheduling of different applications. MAC layer uses this information for scheduling and control purposes [49]. Fig. 6 shows different cognitive functions at network and physical layer, which includes information about channel availability, determination of gain, transmission strategy and application characteristics. It also includes functions like buffer size determination at network layer.

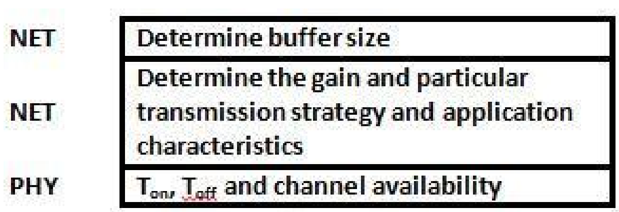

Fig. 6. Functions at Different Levels in Cognitive Radio Networks [49]

VIII. Performance Metrics

The performance evaluation of CR network is of keen importance as it used to check implementation feasibility of CR networks. Formalization of performance metrics will help in the research, comparison and advancement of the **c**ognitive radio algorithms. Performance analysis could be done by applying various performance metrics on CR network. The performance metrics are examined at the node, network and application level [51]. The performance evaluation is a big challenge in the designing of CR networks and devices. The important step in CR design is the selection and establishment of effective performance metrics. The performance metrics will help the integration of the existing wireless networks with the CR based paradigm. It also helps in establishing base for regulating and certifying CR. The vendors also need performance nontrivial, subjective benchmark for the approval and testing during the production and development of the CR networks [13] . The performance bench mark are used by the service providers in the deployment and maintenance of CR network. The CR technologies cannot operate without performance metrics and bench marking methods. The performance metrics must be selected carefully and they must enable the CE to give the proper response to the changing environment and they must have the dynamic situation aware utility functions [13]. The CR performance metrics are sub-divided in to two categories **n**ode level performance metrics (Node Score Card) and **n**etwork level performance metrics (Network Score Card) [51].

The functionality of both CR node and **n**etwork is evaluated on the basis of four domains given below [51]. **For CR node domains are cognitive functions, overall node performance, node complexity and technical maturity. Similarly for CR network domains are cognitive functions, overall network performance, network complexity and technical maturity.**

On the basis of these domains various performance metrics are purposed to test the performance of CR node and **n**etwork.

IX. Conclusion

This paper provides a short summary about the cognitive radios and cognitive networks. Different cognitive radio paradigms and frameworks disscussed in this paper will help in understanding basic concepts of cognative radio netwok. It will also help in future research in the field of CR. It shows that cognitive radios could be used for the solution of problems faced in wireless communication domain.

Acknowledgment

This research is sponsored by Higher **e**ducation **c**ommission (HEC) of Pakistan under PhD Overseas scholarship in the selected fields.

References

[1] Piazza, D., P. Cosman, L.B. Milstein and G. Tartara, 2009. A Resource Allocation Algorithm for Real-Time Streaming in Cognitive Networks. In the proceedings of Wireless Communications and Networking Conference, pp: 1-5.

[2] Yau, K.-L.A, P. Komisarczuk and P.D. Teal, 2009. Cognitive Radio-based Wireless Sensor Networks: Conceptual Design and Open Issues. In the proceedings of 2009 IEEE 34th conference on Local Computer Network, pp: 955-962.

[3] Krishna, T.V. and A. Das, 2009. A Survey on MAC Protocols in OSA Networks. J. of Computer Networks., 53 (9): 1377-1394.

[4] Hossian, M., A. Mahmood, and R. Jantti, 2009. Channel ranking algorithms for cognitive coexistence of IEEE 802.15.4. In the proceedings of 2009 IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications, pp: 112-116.

[5] Marcus, M., C.J. Burtle, B. Franca, A. Lahjouji and N. McNeil, 2002. Federal Communications Commission (FCC): Spectrum Policy Task Force. ET Docket no. 02-135.

[6] Claudio, R. C. M. da S., B. Choi, and K. Kim, 2007. Distributed Spectrum Sensing for Cognitive Radio Systems. In the proceedings of 2007 Information Theory and Applications Workshop, pp: 120-123.

[7] Mitola, J., 2000. Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio, PhD thesis, Royal Institute of Technology (KTH) , Stockholm, Sweden.

[8] Kim, S.J. and G. B. Giannakis, 2009. Rate Optimal and Reduced-Complexity Sequential Sensing Algorithms for Cognitive OFDM Radios. In the proceedings of 2009 43rd annual conference on Information Science and Systems, pp: 141-146.

[9] Maldonado, D., B. Le, A. Hugine, T.W. Rondeau and C.W. Bostian, 2005. Cognitive Radio Applications to Dynamic

Spectrum Allocation: A Discussion and an Illustrative Example. In the proceedings of 2005 First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, pp: 597-600.

[10] Mitola, J., G.Q. Maguire, 1999. Cognitive Radio:

Making Software Radios More Personal. J. of Personal Communication, IEEE., 6 (4): 13-18.

[11] Zhang, Q., G.J.M. Smit, L.T. Smit, A. Kokkeler, F.W. Hoeksema and M. Heskamp, 2005. A Reconfigurable Platform for Cognitive Radio. In the proceedings of 2005 2nd International Conference on Mobile Technology, Applications and Systems, pp: 1-5.

[12] Haykin, S., 2005. Cognitive Radio: Brain-Empowered Wireless Communication. IEEE Journal on Selected Areas in Communications. 23 (2): 201-220.

[13] Molisch, A.F., L.J. Greenstein, M. Shafi, 2009. Propagation Issues for Cognitive Radio. Proceedings of the IEEE., 97 (5): 787-804.

[14] Digham, F.F., 2008. Joint Power and Channel Allocation for Cognitive Radios. In the proceedings of 2008 Wireless Communications and Networking Conference, pp: 882 – 887.

[15] Akyildiz, I. F., W. Y. Lee, M.C. Vuran, S. Mohanty 2006. Next Generation/Dynamic Spectrum Access/Cognitive Radio Wireless Networks: A Survey. Computer Networks: The International Journal of Computer and Telecommunications Networking, 50 (13): 2127-2159.

[16] Alex, Z.C., Sivaraman and S.K. Vasudevan, 2010. Software Defined Radio Implementation (With simulation & analysis). Intl. J. of Computer Applications., 4 (8): 21–27.

[17] Johnson, P., 1985. New Research Lab Leads to Unique Radio Receiver. E-Systems Team., 5 (4): 6-7.

[18] Hoeher, P. and H.Lang, 1988. Coded-8psk Modem for Fixed and Mobile Satellite Services Based on DSP. In the proceedings of 1988 1st International workshop on Digital Signal Processing Techniques Applied to Space Communications, pp: 117-123.

[19] Mitola, J., 2000. Software Defined Radio Architecture Evolution: Foundations, Technology Tradeoffs, and Architecture Implementations. IEICE Transactions on Communications, E83-B (6):1165-1173.

[20] Youngblood, G., 2002. A Software-Defined Radio for the Masses, Part 1"., pp: 1-31.

[21] Jeffrey, H.R., 2002. Software Radio: a modern Approach to Radio Engineering. Prentice Hall, pp: 5-8.

[22] Mitola, J., 1993. Software Radios Survey, Critical Evaluation and Future Directions. Aerospace and Electronic Systems Magazine, IEEE,. 8 (4): 25-36.

[23] Isomäki, P., N. Avessta, 2004. An Overview of Software Defined Radio Technologies. TUCS Technical Report, Turku Centre for Computer Science, No 652.

[24] Gappmyer, Kogler, Course Notes: Software Define Radio, TUGraz, Austria

[25] Huang, Y., J. Wang, H. Jiang, 2010. Modeling of Learning Inference and Decision-Making Engine in Cognitive Radio. In the proceedings of 2010 Second International Conference on Networks Security, Wireless Communications and Trusted Computing, pp: 258 – 261.

[26] Liang, Y.C., Y. Zeng, E.C.Y. Peh, A.T. Hoang, 2008. Sensing Throughput Tradeoff for Cognitive Radio Networks. J. of IEEE Transactions on Wireless Communications., 7 (4): 1326-1337

[27] Ariananda, D.D., M.K. Lakshanan, H. Nikookar, 2009. A Survey on Spectrum Sensing Techniques for Cognitive Radio. In the proceedings of 2009 2nd International workshop Cognitive Radio and Advanced Spectrum Management, pp: 74-79.

[28] Bhattacharya, P.P., R. Khandelwal, R. Gera, A. Agarwal, 2011. Smart Radio Spectrum Management for Cognitive Radio. Intl. J. of Distributed and Parallel Systems (IJDPS)., 2 (4): 12-24.

[29] Zurutuza, N., 2012. Cognitive Radio, Fundamental Performance Analysis for Interweave Opportunistic Access Model. *www.stanford.edu/~naroa/ee359project.pdf*.

[30] Goldsmith, A., S.A. Jafar, I. Maric´, and S. Srinivasa, 2009. Breaking Spectrum Gridlock with Cognitive Radios: An Information Theoretic Perspective. J. of the IEEE., 97 (5): 894-914.

[31] Wang, B., and K. J. Ray Liu, 2011. Advances in Cognitive Radio Networks: A Survey. IEEE J. of Selected Topics in Signal Processing,. 5 (1): 5-23.

[32] Newell, A., 1994. Unified Theories of Cognition. Harward University Press.

[33] Amna, A., J.H. Reed, 2010. Survey of Cognitive Radio Architectures. In the proceedings of 2010 IEEE South East conference, pp: 292-297.

[34] Boyd, J., John Boyd Compendium, [Online]. Available: http://dnipogo.org/john-r-boyd/

[35] Li, S., M. Kokar, 2013. Flexible Adaptation in Cognitive Radios. Springer, pp: 13-15.

[36] Popescu, A., 2012. Cognitive Radio Networks. In the proceedings of 2012 9th International Conference on Communications.

[37] Bryant, D.J., 2004. Modernizing Our Cognitive Model. In the proceedings of 2004 9th International Command and Control Research and Technology Symposium, pp: 1-14.

[38] Mahmoud, Q., 2007. Cognitive Networks: Towards Self-Aware Network. Wiley-Interscience.

[39] Langley, P. and Choi, 2007. A Unified Cognitive Architecture for Physical Agents. In the proceedings of 2007 20th national conference on Artificial Intelligence, Boston, pp: 1469-1474.

[40] Laird, J., 2008. Extending the Soar Cognitive Architecture. In the proceedings of 2008 Artificial General Intelligence Conference, pp: 224-235.

[41] Welcome to ACT-R, 2009 [Online]. Available: http://act-r.psy.cmu.edu/.

[42] Gilboa, I and D. Schmeidler, 2001. A Theory of Case-Based Decisions. Cambridge University Press.

[43] Kolodner, J., 1993. Case-Based Reasoning. Morgan Kaufmann Publisher.

[44] Le, B., F.A.G.Rodriguez, Q. Chen, B.P. Li, F. Ge, M. Elnainay, T.W. Rondeau and C.W. Bostian, 2007. A Public Safety Cognitive Radio Node. In the proceedings of 2007 SDR Forum Technical Conference, Denver, USA.

[45] He, A., J. Gaeddert, K.K. Bae, T.R. Newman, J.H. Reed, L.Morales and C.H Park, 2009. Development of a Case-Based Reasoning Cognitive Engine for IEEE 802.22 WRAN Applications. J. of Mobile Computing and Communications Review., 13 (2): 37-48.

[46] Cordeiro, C., C. Kiran and D. Birru, S. Shankar N., 2006. IEEE 802.22: An Introduction to the First Wireless Standard Based on Cognitive Radios. IEEE journal of Communications. 1 (1): 38-47.

[47] Reed, J., C. Bostian, 2006. Understanding the Issues in Software Defined Cognitive Radio," in Dyspan, Dublin, Ireland.

[48] Stuntebeck, E., T. O'Shea, J. Hecker, T. C. Clancy, 2006. Architecture for an Open-Source Cognitive Radio. In the proceedings of 2006 SDR Forum Conference.

[49] Shankar, S.N., 2007. Squeezing the Most Out of Cognitive Radio: A Joint MAC/PHY Perspective. In the proceedings of 2007 IEEE International Conference on Acoustics, Speech and Signal Processing, pp: 1361-1364.

[50] Cabric, D., S.M. Mishra, R.W. Brodersen, 2004. Implementation Issues in Spectrum Sensing for Cognitive Radios. In the proceedings of 2004 38th Asilmoar Conference on Signal, Systems and Computers, pp: 772-776.

[51] Zhao, Y., S. Mao, J.O. Neel, and J.H. Reed, 2009. Performance Evaluation of Cognitive Radios: Metrics, Utility Functions and Methodology. Invited paper, under review for proceedings of the IEEE Special Issue on Cognitive Radio., 97 (4): 1-15.