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Cognitive Radio-Trends, Scope and Challenges in Radio Network Technology

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Abstract: Cognitive radio is a revolutionary technology that aims for remarkable improvements in efficiency of spectrum usage. It will change the way the radio spectrum is regulated, but also requires new enabling techniques such as improved spectrum sensing and dynamic spectrum assignment. These techniques, together with the software definition for reconfigurable radios, will enable an early and successful roll-out of cognitive radio, which can affect many traditional businesses. Cognitive Radio is an adaptive intelligent radio and network technology that can automatically detect available channels in a wireless spectrum and change transmission parameters enabling more communications to run concurrently and also improve radio operating behaviour without interfering with licensed users. This technology is the focus of a huge amount of modern research and development. In the present paper the authors present a comprehensive overview of the concepts, methods, technologies, issues, scope and challenges of cognitive radio technology.

Keywords: cognitive radio, radio spectrum, transmission spectrum, wireless spectrum, scope and challenges.

I. INTRODUCTION

The natural electromagnetic radio spectrum is licensed to several bodies for various applications. With increasing applications there is suddenly a severe shortage of spectrum. It is found that very little of the licensed spectrum is actually utilized. The unutilized part of the spectrum results in Spectrum holes or White Spaces. Therefore, recently it has been proposed to allow utilization of the unused spectrum at a time to other users who do not hold the license. This will be possible by the Cognitive Radio. Cognitive radio is "a type of radio in which communication systems are aware of their environment and internal state and can make decisions about their radio operating behavior based on that information and predefined objectives" [1]. There are several other definitions of cognitive radio.[2][3] As arranged in order of increasing technology – software capable radio, software programmable radio, software defined radio, aware radio and cognitive radio. [4]The heart of a Cognitive Radio application is in its ability to improve performance through learning. Thus Cognitive Radio is an adaptive intelligent radio and network technology that can automatically detect available channels in a wireless spectrum and change transmission parameters enabling more communications to run concurrently and also improve radio operating behavior. Here the transmission and reception parameters are changed to communicate efficiently without interfering with licensed users. Parameter changes are based on active monitoring of several factors in the radio environment .These factors are roughly i) waveform protocol ii) operating frequency protocol and iii) networking. [5]This functions as an autonomous unit in the communications environment, exchanging information about the environment with the networks it accesses and other cognitive radios. A Cognitive Radio monitors its own performance continuously, in addition to reading the radio's outputs; it then uses this information to determine the Radio environment, channel conditions, link performance, etc., and adjusts the radio's settings to deliver the required quality of service subject to an appropriate combination of user requirements, operational limitations, and regulatory constraints. They typically operate at frequencies that were originally licensed to other (incumbent, primary) radio services, and in addition at available frequencies in unlicensed bands. A cognitive radio, however, is not necessarily restricted to the existing licensing for primary radio systems, and operates at any unused frequency, whether or not the frequency is assigned to licensed, primary services. This is referred to as overlay sharing[6], which obviously requires new protocols and algorithms for spectrum sharing. It also involves important regulatory aspects: Cognitive radios must not interfere with the operation of licensed radio systems when identifying spectrum opportunities and during operation in licensed spectrum. Cognitive radios hold tremendous promise for increasing spectral efficiency in wireless systems as an intelligent wireless communication device that exploits side information about its environment to improve spectrum utilization through a learning process.[7]

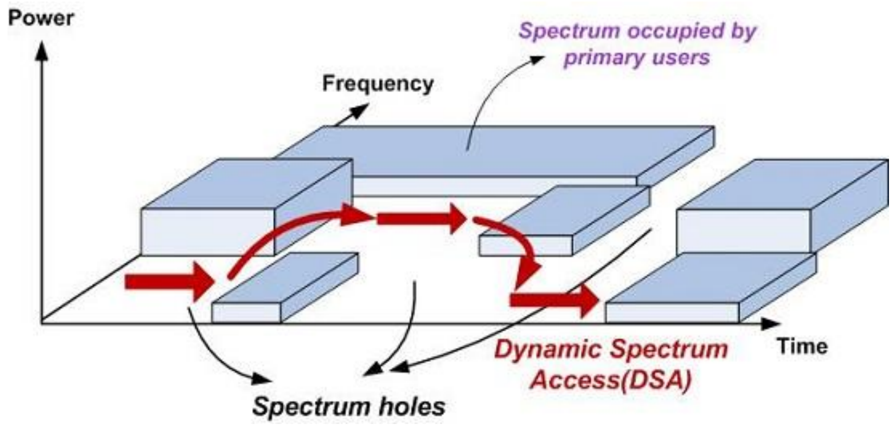

Fig. 1 Fundamental Principle of Cognitive Radio

The figure above depicts the presence of white spaces in the allotted frequency bands, cognitive radio technology aims at intelligently utilizing these white spaces without causing disturbance to the primary users.

II. EVOLUTION OF COGNITIVE RADIO

The concept of cognitive radio was first proposed by Joseph Mitola III at KTH (the Royal Institute of Technology in Stockholm) in 1998. He published an article (jointly by Joseph Mitola and Gerald O.Maguire Jr.) in 1999.As described in the article 'The point in which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of Use context, and to provide radio resources and wireless services most appropriate to those needs".[38]

In November 2002, the Federal Communications Commission (FCC) published a report prepared by the Spectrum-Policy Task Force which aimed at improving how the electromagnetic spectrum was utilized in the US.[40]The task force was made up of a team of multidisciplinary professionals from the commission's bureaus and offices. Among the task force major findings and recommendations, the second finding on page 3 of the report revealed that "In many bands, spectrum access is a more significant problem than physical scarcity of spectrum, in large part due to legacy command-and-control regulation that limits the ability of potential spectrum users to obtain such access." Cognitive radio paved the path for effective utilization of the white spaces in the radio bands thus improving the use of electromagnetic spectrum. Traditional regulatory structures have been built for an analog model and are not optimized for cognitive radio. Regulatory bodies in the world (including the Federal Communications Commission in the United States and Ofcom, the communications regulator in the United Kingdom) as well as different independent measurement campaigns found that most radio frequency spectrum was inefficiently utilized.[39] Cellular network bands are overloaded in most parts of the world, but other frequency bands (such as military, amateur radio and paging frequencies) are insufficiently utilized. Independent studies performed in some countries confirmed that observation, and concluded that spectrum utilization depends on time and place. Moreover, fixed spectrum allocation prevents rarely used frequencies (those assigned to specific services) from being used, even when any unlicensed users would not cause noticeable interference to the assigned service. Regulatory bodies in the world have been considering whether to allow unlicensed users in licensed bands if they would not cause any interference to licensed users. These initiatives have led to cognitive-radio research on dynamic spectrum access.

Simon Haykin in 2005 defined cognitive radio as brain-Empowered Wireless Communications gave the definition of 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, with two primary objectives in mind highly reliable communication whenever and wherever needed; efficient utilization of the radio spectrum” .

Since then, FCC pushed towards advances in technology for more efficient spectrum usage, and using CR technology to facilitate the flexible, efficient, and reliable use of spectrum gained momentum in both industry and academics. FCC proponed the use of concepts such as dynamic frequency selection (DFS)[42],incumbent profile detection, and transmit power control for CRs. In 2004, FCC issued a notice of proposed rulemaking, which introduced the possibility of allowing the unlicensed (or secondary) users to temporarily use spectrums allocated to licensed (or primary) users as long as the secondary users do not cause harmful interference to primary users. An important milestone in the development of CR is the approval by FCC in November 2008 of the unlicensed use of the TV white space (TVWS; 54–72,76–88,174–216, and 470–806 MHz) based on spectrum sensing as well as consultation with an FCC-mandated database [43].These spectrum bands are attractive because of their superior radio propagation characteristics in the sub-gigahertz frequencies. In September 2010, FCC released new rules for the use of white space for unlicensed wireless devices, which removed the mandatory sensing requirements and thus facilitated the use of the spectrum with geo-location based channel allocation [44]. This led to the motivation of new wireless standards and standardization initiatives including the IEEE 802.22 for wireless regional area networks (WRANs), the European Computer Manufacturers Association 392 for personal portable devices, and the IEEE 802.11af and 802.19.1 Task Groups. In the last decade, there has been a significant amount of research work focusing on the different aspects of CRNs such as spectrum sensing and signal classification techniques at the PHY; scheduling, transmission power control, and adaptive channel access protocols at the link layer; resource allocation for multi-hop transmission at the routing layer; modeling and analysis of security; and CRN economics. In addition to a huge number of research papers, a number of research monographs and edited books [45–53] have appeared. A number of special issues on CR have been organized in both IEEE and non-IEEE journals [54–66].

III. Architecture Of Cognitive Radio

To discuss the building blocks of the various types of cognitive radio should be considered. A cognitive radio network may either be cooperative or non-cooperative in nature. In the non cooperative CRN architecture, each cognitive node is autonomous. Therefore, it has minimal communication requirements and thus less overhead of information; however, the spectrum utilization may be low. On the other hand, in the cooperative but centralized CRN architecture, a centralized server maintains a database of spectrum availability and access information as received from the group of secondary users. So in this case the spectrum management is not only disciplined but also easier to handle. The nodes usually exchange information among themselves periodically.

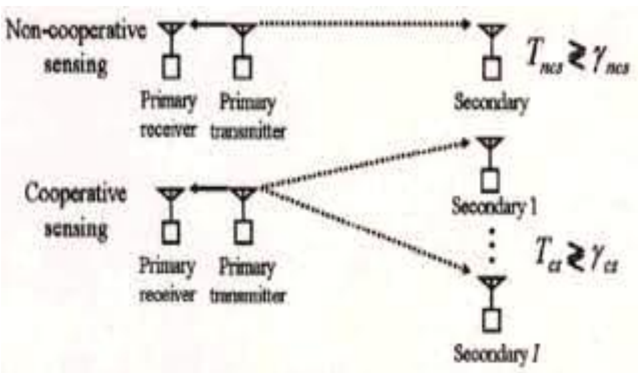

Fig. 1 Non cooperative and cooperative sensing

The CRN uses local as well as global information to maintain a global optimal performance. The network performance sometimes suffers from the hidden node problem and large control overhead. The hidden terminal problem occurs when a node is visible from the access point but cannot communicate to the nodes within communication distance. [54]

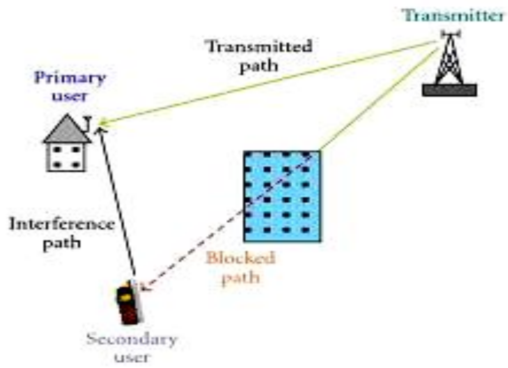

Fig. 3 Hidden Node Problem

In both centralized and distributed strategies, the primary user may or may not cooperate. The communication protocols at the different layers need to function such that the utilization of the radio spectrum is maximized while satisfying the policy constraints.

The different techniques of spectrum sensing have different implementation complexities. From a layered outlook a cognitive radio architecture can be described to consist of

1. Physical Layer ii) MAC Layer ii) Network Layer and iv) Transport Layer
2. Physical Layer-In the Physical layer spectrum sensing is the primary task, which includes functionalities such as detecting spectrum holes/opportunities over wide-frequency spectrum, estimating opportunity, estimating interference at the primary receiver (e.g., in a CDMA environment)[55]
3. MAC Layer- MAC layer: In the MAC layer, a decision is taken on whether transmission should be carried out or not considering that the spectrum sensing could be faulty and the process of utilizing the spectrum holes (e.g., what modulation and power level to use) and, in case of transmission, on how to share the spectrum with other CRs. The MAC protocol functionalities also include obtaining information on channel occupancy (spectrum sensing) and making decisions on spectrum access, synchronizing transmission parameters (e.g., channel and time slot) between the transmitter and receiver, allowing concilation among primary users and secondary users for spectrum allocation, allowing communication among secondary users to perform channel sensing and channel access and spectrum trading functions (e.g., spectrum bidding and spectrum pricing[56]).
4. Network Layer-: The primary tasks at the network layer are constructing topology, addressing, and routing. The topology construction involves spectrum detection, neighbor discovery, and topology management (e.g., through spectrum mobility.)[54]
5. Transport Layer-The transport layer protocol is responsible for flow and congestion control, the performance of which is affected by MAC protocol performance and spectrum mobility. The throughput of the transmission control protocol is largely affected by the spectrum management techniques.

The adaptive protocols in the layers depends on the CR environment, the traffic between primary and secondary users, the spectrum hole width etc.

A software-defined radio has several major sub-systems, but is essentially a distributed computing system. In this section, the major sub-systems are discussed.

RF Front End [8]

A SDR requires a general purpose RF front end[9]. This typically requires a wide tuning range, ideally it tunes from DC to light notwithstanding the technical problems. A pre-selector / power amplifier allows the selection of a subset of the spectrum, and either tunable filters or fixed filters are used for this purpose. The architecture is discussed here. A Rx or Tx chain processes the radio signal in the analog domain. These chains may be combined into a single, bi-directional path at design time. Finally, a synthesizer is required to generate the local oscillators for processing. The analog processing is software configurable through the setting of switches to select filters and through the setting of registers to control mixer frequencies. One of the most critical architectural features in a SDR is the software structure or software architecture. Artificial Intelligence techniques enable such changed behavior. An agent is an entity that perceives and acts, and an agent model correct for a Cognitive Radio application. There is a continuum of sophistication in agent architecture. There are mainly four classes of agents [8]

1. Simple Reflex Agent- Agent selects its action as a function of the current percept and uses combinational logic.
2. Radio Agent With State: Agent maintains internal state memory as a function of percept history and partially reflects unobserved aspects. It is always just not a set of percept though.
3. Goal Based –Goal information identifies states that are desirable . Sometimes simple steps help to reach the goal and at times multiple complex steps might be needed.
4. Utility Function maps state sequence to real number. Real number is the relative happiness of the agent and allows rational decisions in some case where percept is inadequate.

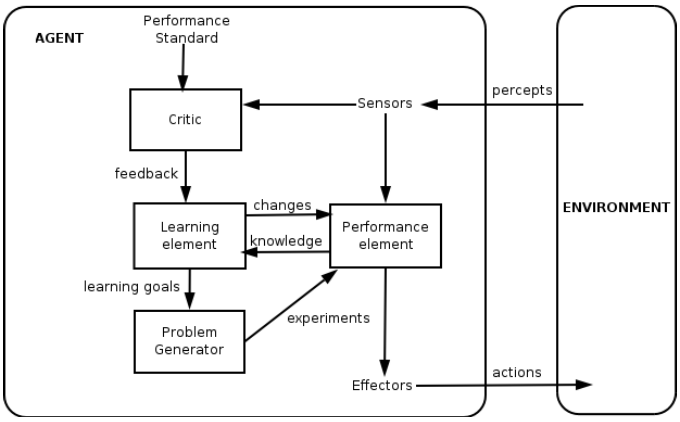

Fig. 4 Role of Agent in Cognitive Environment

Genetic algorithm [11] and neural engineering techniques [12] may be used to explore the possible relationships between percept and good actions. There are several search techniques employed for this. In a cognitive radio model other actuators and sensors may also be present other than the normal Rx receiver and Tx transmitter circuit. The cognitive learning techniques in cognitive radio use several observations and draw conclusions from a set of inputs that produces certain outputs and thus concludes on a particular desired behavior. It basically uses inductive learning. When multiple predictions, extracted from an environmental model, are combined, the process is called ensemble learning. An inductive learning system that includes background knowledge has potential for better performance when compared to a pure inductive learning system because it starts in a better situation. Any fielded CR will have an initial set of knowledge. The reinforcement of actions from feedback is essential for reinforcement learning. Statistical models of learning include Bayesian computations of probability as a function of the percept. Self organizing maps, such as Kohonen[13] networks or Back propagation Neural Networks, are also considered statistical learning due to the training trials.

The MODEM subsystem[10] accomplishes the modulation and demodulation of the data stream using digital methods. In high performance MODEMs FPGA processing resources are usually needed to accommodate high sample rates. FPGAs are programmed in hardware definition languages such as VHDL or Verilog. For more SW portability or for floating point signal processing, DSP resources are programmed in assembly or high level programming languages. A general MODEM architecture is described as follows:- [17]

Format A/D→Source Encode→Encrypt→Channel Encode→Multiplex→Pulse Modulation→Band pass Modulation→Frequency Spread→Multiple Access→Transmit------------→Synchronization between transmitter and receiver----------→Format D/A→Source Decode→Decrypt→Channel Decode→Demultiplex→Pulse Demodulation→Band pass Demodulation→Frequency Dispread→Multiple Access→Receive

Types Of Cognitive Radio

There are basically two types of cognitive radio, full Cognitive Radio (Mitola Radio)[2] and the spectrum sensing radio. The full cognitive radio takes all the parameters into account while the spectrum sensing radio only takes the radio frequency into account. The main area of research concerning cognitive radio is to design high quality spectrum sensing devices and algorithms to measure and record spectrum sensing data between nodes for the construction of cognitive radio. The main functions involved in a spectrum sensing cognitive radio are spectrum sensing, spectrum management, spectrum mobility and spectrum sharing.

The diagram below depicts how a cognitive radio works.

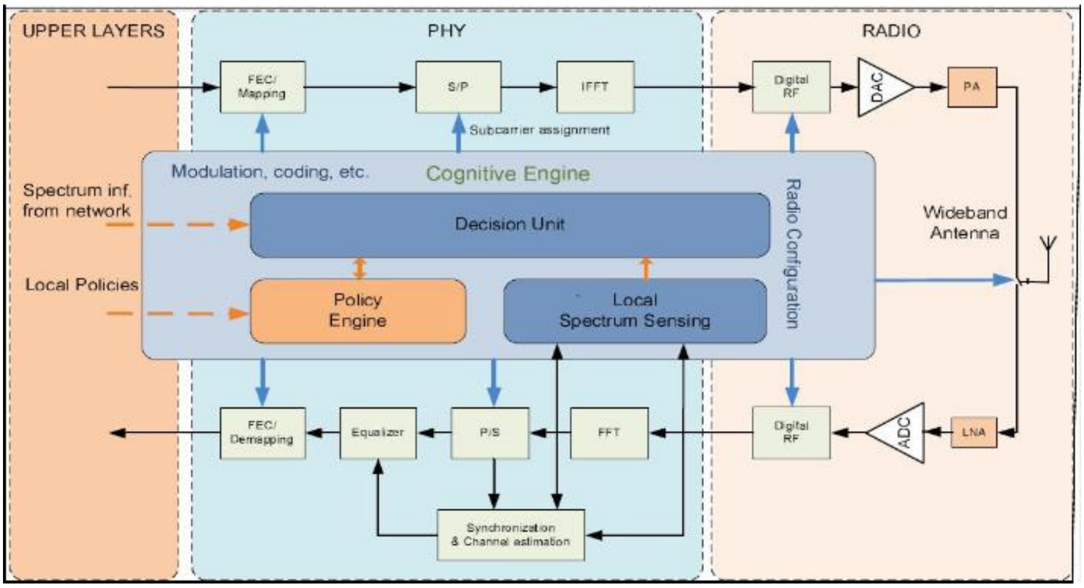

Fig. 4 Working Of Cognitive Radio

Spectrum Sensing Techniques

Cognitive radio basically works by making fundamental changes in the way radio spectrum is regulated. Basically we are focusing on horizontal and vertical spectrum sharing[14].Cognitive radios share spectrum with radio systems that are designed to access spectrum with different priorities based on the regulatory status of radios working within the same spectrum. The spectrums are named primary and secondary based on their priority, licensed radio systems are those have specially assigned bands and unlicensed radio systems are designed to live with some interference. Sharing with primary radio systems is referred to as vertical sharing, and sharing with secondary radio systems is referred to as horizontal sharing. Apparently, dissimilar cognitive radios that are not designed to communicate with each other may also share the same spectrum. This is another common example of horizontal sharing, because the dissimilar cognitive radio systems have the same regulatory status, i.e. similar rights to access the spectrum. The main work of the cognitive radio is to find out the unutilized spectrum. Opportunities keep changing over time and it is needless to say that that vertical sharing is more stringent than horizontal sharing. So "spectrum etiquettes"[15] and "value orientation"[16] are useful to control unpredictable uses. High transmission powers for large coverage areas in a particular broadcast area are used to guarantee reliable reception, so receivers close to the broadcast site have such high power that a little interference by cognitive radios in the vicinity cannot create much disturbance. It might therefore help to allow reuse of the broadcast band for cognitive radios after scanning for spectrum opportunities and change in scenario.

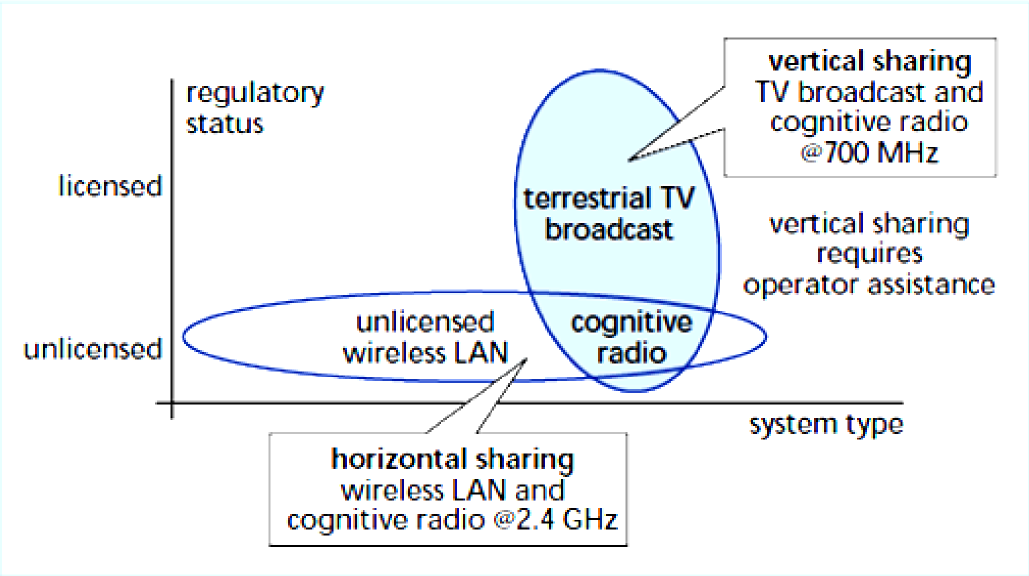

Fig. 5 Horizontal and vertical spectrum sharing techniques

Spectrum Sensing Methods

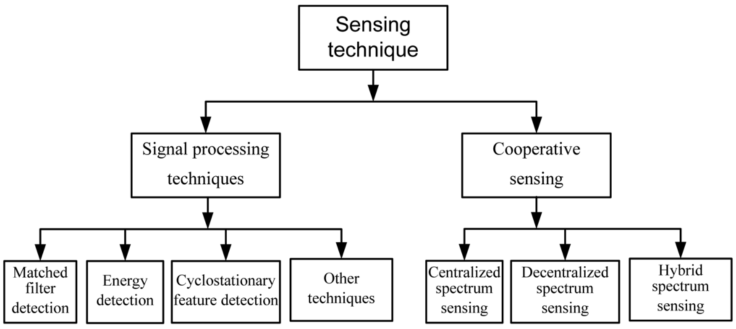

Fig. 6 various spectrum sensing techniques

There are different types of spectrum sensing methods: transmitter detection, co-operative detection and interference detection.

In transmitter detection, the usage of the spectrum is determined by checking whether the signal from a primary transmitter is present in the spectrum. This can be done using three techniques:

Matched Filtering, Energy Detection and Cyclostationary detection.[18]

Matched Filtering [19] uses prior knowledge of the primary user's waveform to determine whether the spectrum is in use.

Energy Detection measures the energy received from the primary user to detect usage of the spectrum.[20]

In cyclostationary detection [21] the obtained information varies statistically over time and situation. Many signals exhibit periodicities of their statistical parameters when it undergoes operation such as sampling, multiplexing, modulating and coding. These cyclostationary properties named as special correlation features are used for detection. Also, detection in case of cognitive radios is not limited to a particular band of choice but must detect the entire network for interference.

In cooperative sensing, the secondary users accumulate their measurements of the energy levels of the spectrum and collectively decide when the spectrum is in use. An example of a sensing technique is the CUSUM algorithm [22], which uses sequential detection techniques to determine the spectrum usage based on the readings from all the secondary users and also the past usage data. An improvement on the CUSUM algorithm is DualCUSUM [23], which is implemented in two stages. The first step determines whether the spectrum is in use locally, and the second step propagates the information to the fusion center if a change is detected, where the calculations are done to determine whether the spectrum is in use.

Several Tools for sdr and cognitive radio design

High level design of radios mainly includes certain tools that allow control and reconfiguration of the software defined radio system with a high level of abstraction. GNU Radio is an open source software development toolkit for software radio applications [24] that runs on general purpose processors (GPPs) that allows reuse of existing signal processing components through Python scripts. OSSIES which is an SCA implementation an interoperable, multiplatform architecture framework for software radio systems and it mainly uses DSP as the main processor. Iris is a decision Engine that can be implemented by the user to subscribe and react to events triggered by radio components. Reactions can comprise of anything from diagnostic output to full reconfiguration of the radio application. Currently a more efficient version of the Iris is under construction. Low-Level

Design frameworks provides tools and application programming interfaces (APIs) at a lower level meaning that they provide a ground up approach using programming and hardware development languages. Since no generic or reusable libraries are referred it is a more non aligned approach to the radio implementation, the signal processing and also reconfiguration. But it is needless to ay that it requires more expertise and effort.

Wireless Open-Access Research Platform (WARP) is a scalable, extensible and programmable hardware platform with a Xilinx Virtex-II Pro FPGA as its baseband processor. The physical layer of a radio is implemented in the FPGA logic fabric, while MAC layer functionality can be implemented in C using the embedded PowerPC processor cores (without an operating system). In October 2009 a new version of the WARP board was released featuring the more powerful Virtex4 FPGA and Gigabit Ethernet connectivity []. Standard Xilinx tools are used to program the WARP board and significant hardware expertise is required to take advantage of the WARP platform [25]. Lyretech is also an example of such a tool that can be used for SDR designs. Kansas University Agile Radio(KUAR) [26]is an experimentation platform for cognitive radio.INLAB Network Centric Cognitive Radio (WiNC2R) is a cognitive radio platform that uses flexible hardware accelerators to achieve programmability and high performance at each layer of the protocol stack but this is still at an early age of development..

TABLE I
Summary of Discussed Platforms

	Design	Reconfiguration	Comp.	Defines	Reatime
	Level	Runtime	Tools[1]	MoC	Hardware
GNURadio	high			x x	x
OSSIE	high	x	2	x 3	
IRIS	high				
WARP	low	x	X	x x	
LyreTech	low	x	X	x	
KUAR	low			x	
WiNC2R	low				

: fully supported; : partly supported; × : not supported xx;

[1]high-level radio composition tools, to assemble a full system

[2]the design framework does not include cognition [3]will be supported in future release [100]

IV. COGNITIVE LEARNING IN COGNITIVE RADIO

Cognition literally means the mental action of acquiring knowledge and understanding through thought experience and the senses. Cognitive radio is named so because it acquires intelligence through learning methods and adapts dynamically as required .Cognitive reasoning is a focal aspect of cognitive radio networks. It fosters the development and/or the extraction of contextual and environmental awareness towards an optimal solution to a particular problem. A reasoning output would then be a timely and intelligent answer to a problem set based on previous actions and consequences, current observations and objectives, and the descriptions of the used data-types. Learning mechanisms are responsible for building up knowledge and knowledge bases .Thus observation, orientation; inference and implementation form the basics of the cognitive cycle. These trigger the way to an actionable decision. The inference is enabled by reasoning mechanisms which is optimally platform independent .Therefore, the Perception and Action Abstraction Layer (PAAL)[27] is introduced as a mediator that allows translation of the SDR observables and the actions into a platform-independent knowledge representation. The acquired knowledge also necessitates independence from the potential application. As a result, the Ontology and Rule Abstraction Layer (ORAL)[27] is foreseen as a presenter of knowledge (i.e. ontology and rules) in a platform-independent implementation manner. Finally, the Knowledge Base (KB) stores the acquired knowledge and the set of actions that were or are to be executed.

V. INFLUENCE OF MACHINE LEARNING AND GAME THEORY IN COGNITIVE RADIO TECHNOLOGY

The process of learning in a cognitive radio is based on the rudimental concept of machine learning and game theory. The application of machine learning techniques [28] to cognitive networks and game theoretic analysis of simple adaptation mechanisms can be shown to converge to equilibrium such as Nash equilibrium [29] or one of its variations in cooperative and non-cooperative scenarios. Game theory is the study of mathematical models of conflict and cooperation between intelligent rational decision-makers. The parallel to cognitive networks should be clear: in many game theoretic models of cognitive networks, the players in the game are the cognitive radios that form the network. These radios take actions such as setting their transmit power or selecting a channel in which to operate. Such actions are based on the radio's observations of its environment (e.g., channel availability, frame error rate, or interference). As time progresses, a radio can learn from the outcome of its past actions and from observing the actions of other radios in the network, and modify its actions accordingly. The simplest game theoretic method that best captures the relevance of it in cognitive radio is the concept of repeated game (it essentially works on the concept of Nash Equilibrium). The cognitive radio process is often described by the OODA loop (observe-orient-decide-act). A simple example may be considered at this point. Let us consider a number of cognitive radios competing for channels that are available. Cognitive radio i observes other radios' actions at the kth stage: these actions are collected into a history vector. The history vectors for all previous stages are considered during the orientation step. The radio then decides on an action by applying a strategy that maps from the set of histories to the radio's action set. Finally, the radio performs an action during the (k +1)th stage of the repeated game, and the cycle repeats. Mapping this problem into the repeated games formulation, the radios are the players in the game, their action is the selection of one of C channels, and these selections may depend on the history of primary user activity, as well as on the pattern of channel utilization by other secondary users (for example, a channel that has a history of being frequently occupied by the primary may be avoided by all secondary users). The well-known concept of Nash equilibrium is readily applied to repeated games: In a Nash equilibrium strategy profile, no player can unilaterally increase her expected payoff by selecting a different strategy. Channel selection in opportunistic spectrum access has also often been modeled as a repeated game. Wu et al.[30] model the sharing of open spectrum as a repeated game; they consider a punishment scheme and show that a more efficient equilibrium can be reached when autonomous radios interact repeatedly, as opposed to when they interact in a single stage game (in general, a well known result in game theory, an example of which is the repeated Prisoner's Dilemma). They go further and also consider incentives for cognitive radios to truthfully report their operating conditions in negotiating access to spectrum, relying on mechanism design. The selection of the best spectrum opportunities by secondary users of some spectrum band is modeled as a repeated game. In that model, secondary users will have to vacate their current channel whenever a primary user becomes active, and the authors consider a cost associated with switching channels. A sub game perfect equilibrium, a Nash Equilibrium that is also an equilibrium for every proper sub game of the original game, is one way to characterize the likely outcome of such a game Repeated games have been used to model the evolution of reputation among secondary users, when one of them is chosen to manage the spectrum made available by the primary user. In several of the applications above, repeated interactions among a set of cognitive radios allow for the design of incentive mechanisms that lead to a more efficient equilibrium. A different question is whether there are simple ways for radios, by observing others' actions and the utility resulting from its own actions, to converge to a Nash equilibrium. Unlike repeated games, potential game theory takes previous actions into account. In best reply strategy, one player is offered the opportunity to take action and is said to follow a best reply strategy if her selected action maximizes her utility, given the other players' current actions. With a better reply strategy, the player will always select an action that provides an improvement in utility with respect to her previous action, again given the other players' current actions. For example, when the utility function of each radio considers the social welfare of the network (e.g., by attributing a cost to the radio from interference caused to others, as well as interference suffered from others), a potential function naturally emerges. During channel selection, players have utility functions that reflect their own selfish interests, rather than those of the network. In a number of cases of interest to dynamic spectrum access and cognitive network games, the model results in a potential game. For example, a topology control mechanism in an ad-hoc network consists of two phases: in the first phase, radios select a transmit power level with energy efficiency and network connectivity in mind; in the second, they select channels, with interference minimization objectives.

1. Reinforcement Learning Techniques

In a multi-agent environment, mapping between situations and corresponding actions using supervised learning is practically impossible because the environment is dynamic. Reinforcement learning techniques are much more versatile and are applicable in multi-agent scenarios. They allow the agents to autonomously discover the situation-action mapping through a mechanism of trial and error. An RL agent learns by exploring the available actions and refining its behaviour using only an evaluative feedback, referred to as the reward. Generally an agent is expected not just to take into account the immediate reward, but also to evaluate the consequences of its actions on the future in order to maximize its long-term performance. Delayed reward and trial-and-error constitute the two most significant features of RL. [31]Cognitive frameworks are generally classified into being basic or stemming from the unified theory of cognition [32]. The basic ones can be symbolic, connectionist or hybrid. The frameworks stemming from the unified theory of cognition can be either simple, e.g. Observe-Orient-Decide-Act (OODA) and Critique-Explore-Compare-Adapt (CECA), or complex, e.g. SOAR, Storm and ACT-R [33].The OODA framework relies on a feedback loop to model adaptations to changing environmental conditions. The reasoning, i.e. the decision-making, involves identification of the available hardware configuration changes, identification of the best option to meet the new situation and implementation of the reconfiguration changes on the hardware in a constant feedback loop. The CECA framework expands the OODA framework to adequately describe a proactive decision-making process. The reasoning here is based on social cognition, i.e. multiple entities working on complex problems. This framework does not rely on reactive external observations, but focuses on proactive goal-oriented situations. Both OODA and CECA frameworks are applicable in cognitive radio networks. The SOAR framework is a complex and powerful software suite designed to approximate rational behaviour. Its complexity limits its application in cognitive radio networks. The ACT-R framework theorizes the way human cognition functions. It allows users to represent tasks and measure the time to perform a task and the accuracy of a task. This has potential application to decision-making in cognitive radio networks.

2. Reasoning Types

There is a lack of straightforward logical categorization of the reasoning types in the cognitive networking world, as a result of the technical implementation peculiarities of a particular cognitive networking solution and the corresponding limitations, as well as of the potential applications and the corresponding requirements. Some of the relevant reasoning types in cognitive networking are: proactive, reactive, inductive, deductive, one-shot, sequential, centralized and distributed.

Some reasoning methods in the cognitive networking world are:

Distributed constraint reasoning –This is further classified as Distributed Constraint Satisfaction Problem (DisCSP) or Distributed Constraint Optimization Problem (DCOP). The former attempts to find any of a set of solutions that meets a set of constraints, whereas the latter attempts to find an optimal solution to a set of cost functions

Bayesian networks - a method of reasoning under uncertainty that can be a result of limited observations, noisy observations, unobservable states, or uncertain relationships between inputs, states, and outputs within a system.

Meta heuristics - an optimization method that teams simpler search mechanisms with a higher-level strategy that guides the search.

Heuristics - a method that exploits problem-specific attributes and may lead to increased performance.

3. Reasoning Realizations

This concerns combining a specific reasoning type with a specific reasoning method instantiates a specific reasoning realization that can be effectively deployed in a cognitive networking context. Some of the most relevant reasoning realizations are mentioned below.

1. Case-Based Reasoning (CBR).[34] CBR is a combination of reasoning and learning. The knowledge base is termed as the case base, where cases are representations of past experiences and their outcomes. The case base possesses a structured content in order to be easily shared among different entities within the cognition process and the cognitive network itself (termed agents).
2. Sub-sumption reasoning. Sub-sumption reasoning [34] essentially represents a decomposition of the target goal into smaller sub-goals and ideally with regard to their complexity. The decomposition leads to a set of layered modules operating in parallel that build upon each other, i.e. a hierarchical approach.
3. Fuzzy logic reasoning. Fuzzy logic reasoning [34] relies on Fuzzy Logic (FL), which is a multi-valued logic that allows intermediate values to be defined between conventional evaluations like true/false, yes/no, high/low, etc. One of the most promising approaches to providing FL-assisted reasoning in cognitive radio networks is the usage of Fuzzy Cognitive Maps (FCMs) [34]. FCMs represent a means for modelling systems through the causal relationships that characterize them.
4. Relational reasoning. Relational reasoning [34] relies on the relational structure of propositional knowledge and the semantic features of objects and relational roles. It is enabled by the notion of similarity, which is a fundamental construct in cognitive science and inherently possesses featured and relational aspects.

VI. Issues In Implementation Of Cognitive Radio

There are several issues [35] that might crop up during cognitive radio implementation. These include readiness of the CRN backbone, defining point of Interconnect and Interface, definition of uniform service based priorities, default service and routing requirement, service authentication and authorization.

Some regulatory issues include migration from service based licensing to service neutral licensing regime, issues related with converged licensing, re-classification of the licenses, pricing issues to end users, revenue settlement of the operators in CRN environment. Issues regarding Quality of Service (QoS) are defining QoS parameters, monitoring QoS in various networks and ensuring compliance to pre-defined parameters, ensuring end-to-end QoS across the networks, need to define unique service-based priorities and reliability across diverse applications. Security issues [36] include protection from various protocol attacks, application attacks, unauthorized user introduction, unauthorized access to system data and Denial of Service (DoS) and Distributed Denial of Service (DDoS) [37] attacks. In cognitive radio, a selfish or malicious user can modify its air interface to mimic a primary user. Hence, it can mislead the spectrum sensing performed by legitimate primary users. Such a behavior or attack is termed as primary user emulation (PUE) attack. Its harmful effects on the cognitive radio network are investigated. The position of the transmitter is used for identifying an attacker. A more challenging problem is to develop effective countermeasures once an attack is identified in the cognitive radio network. Public key encryption based primary user identification is proposed in [85] to prevent secondary users masquerading as primary users. Legitimate primary users are required to transmit an encrypted value (signature) along with their transmissions which is generated using a private key. This signature is, then, used for validating the primary user. This method, however, can only be used with digital modulations. Furthermore, secondary users should have the capability to synchronize and demodulate primary users' signal.

VII. Results And Discussions

The main areas of research concerning cognitive radio include spectrum sensing, advance spectrum management ,unlicensed spectrum usage ,spectrum sharing strategies hidden node and sharing issues, trusted Access and Security, Cross Layer Design of the cognitive radio model, hardware and software architecture. This section depicts some of the experiments concerning cognitive radio technology that have been carried out.. Test beds or cognitive components such as IRIS are highly beneficial when conducting cognitive radio experiments as it allows us to simulate a wide range of networks as well as giving us a highly flexible architecture to manipulate based on intelligent observations made about its surroundings. Test beds such as LOG-a-TEC provide outdoor experimental platform, it uses the GRASS-RaPlaT tool in order to provide a virtual experiment planning via simulation in order to ascertain best results as well as support post processing and visualization of experiment results. Several such test beds are VSN,ISM,TVWS,TWIST etc.

In [84] Adaptive coding receiver data plane synthesized for an FPGA platform with one customizable processing region has been used in CR implementation ,a mode switch is mapped to hardware reconfiguration and power consumption is measured with linear regression curves. The model describes radio behavior, including possible reconfigurations independent of the target platform. Correctness checks have been presented, allowing error detection at design-time. It has been shown that the model can be transformed to confirm to a variety of target platforms. Automatic tools take the high-level model and creating a specific implementation for a chosen target platform. An FPGA-based port of the Iris software radio has been chosen as a demonstrator platform. An adaptive coding and sensing cognitive radio was successfully developed using the proposed techniques in this article, underlining the applicability to real systems. With this approach, radio developers do not require detailed platform knowledge, the development process requires less manual effort, and the design can be easily ported to other target platforms.

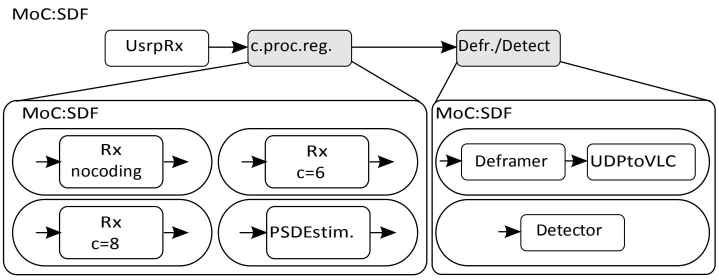

Fig. 9 Synthesised adaptive coding receiver with sensing mode (data plane).

The model is transformed to map to one customisable processing subsystem on the FPGA and another in software.

The proposed model-based design technique is suitable for developing real cognitive radios. It can be used for FPGAbased embedded systems, combining hardware and software components, as well as for pure software platform for real time cognitive radio design.

In [81] the author discusses prototyping to test key ideas of spectrum sensing in a real wireless environment and to highlight difficulties in implementing a sensor device. Since it is illegal to utilize a licensed spectrum for testing purposes, UNII bands have been used as a test bed. The experiment and results concerning implementation of Incumbent Detection with the Atheros Platform has been discussed. Implementation of secondary traffic characterization, priority based scheduling of sensing has also been deliberated. The ultimate results of the experiment mentioned can culminate into a guideline for CR implementation. It proves that detection threshold for incumbent detection has to be chosen by considering the characteristics of the signal such as duty cycle, ON/OFF etc. Secondary traffic being a very important factor a multidimensional vector must be used to describe channel characteristics. To minimize in band interference in this regard it was suggested that no more than RSSI +72 should be introduced to the sensor. For out band interference issues it was concluded that no two WLAN should be placed too close and maximum transmission power should be regulated. Table-I in [81] can be referred for experimental results.

In [82] the challenges associated with spectrum sensing have been reviewed, statistical modeling of network traffic and utilization of these models for network traffic and utilization of these models for prediction of primary user behavior is studied. The performance measure of energy detector based sensing know as radiometry or period-o- gram has been calculated by the author summarized as two probabilities: probability of detection PD and probability of false alarm PF . PD is the probability of detecting a signal on the considered frequency when it truly is present. Thus, a large detection probability is desired. It can be formulated as

$$P_D = \Pr(M > \lambda_E | H1). \quad (1)$$

PF is the probability that the test incorrectly decides that the considered frequency is occupied when it actually is not, and it can be written as

$$PF = \Pr(M > \lambda E | H0). \quad (2)$$

where (H0 , H1) are hypothesis such that

$$H0: y(n) = w(n) \quad (3)$$

$$H1: y(n) = s(n) + w(n) \quad (4)$$

and s(n) refers to signal to be detected and w(n) refers to additive white Gaussian noise. Finally for energy detection method the probabilities PF and PD can be calculated as [41]

$$P_F = 1 - \Gamma\left(L_f L_t, \frac{\lambda_E}{\sigma_w^2}\right), \quad (5)$$

$$P_D = 1 - \Gamma\left(L_f L_t, \frac{\lambda_E}{\sigma_w^2 + \sigma_s^2}\right) \quad (6)$$

where λE is the decision threshold, and Γ (a, x) is the incomplete gamma function as given in [86] (ref. Equation 6.5.1). In order to compare the performances for different threshold values, receiver operating characteristic (ROC) curves can be used. ROC curves allow us to explore the relationship between the sensitivity (probability of detection) and specificity (false alarm rate) of a sensing method for a variety of different thresholds, thus allowing the determination of an optimal threshold. The following figure shows the ROC curves for different SNR values. SNR is defined as the ratio of the primary user's signal power to noise power, i.e. SNR= σ_s^2/σ_w^2. The number of used samples is set to 15 in this figure, i.e. N = 15. The following figure clearly shows that the performance of the threshold detector increases at high SNR values.

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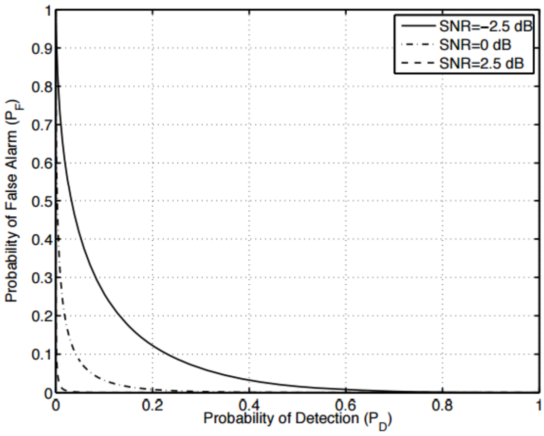

Fig. 7 ROC curves for energy detection based spectrum sensing for different SNR values.

Similarly, for waveform-based sensing metric can be obtained as [87]

$$M = \mathcal{R}e\left[\sum_{n=1}^{N} y(n)s^*(n)\right] \quad (7)$$

Where $*$ represents the conjugation operation. In the absence of the primary user, the metric value becomes

$$M = \mathcal{R}e\left[\sum_{n=1}^{N} w(n)s^*(n)\right] \quad (8)$$

The detailed derivation is available in [87] the decision on the presence of a primary user signal can be made by comparing the decision metric M against a fixed thresholdλ_W.

For cyclostationary detection technique, the cyclic spectral density (CSD) function of a received signal (1) can be calculated as [80]

$$S(f,\alpha) = \sum_{\tau=-\infty}^{\infty} R_y^{\alpha}(\tau)e^{-j2\pi f\tau} \quad (9)$$

where $R_y^{\alpha}(\tau) = E\left[y(n+\tau)y^*(n-\tau)e^{j2\pi\alpha n}\right]$ (10)

is the cyclic autocorrelation function (CAF) and α is the cyclic frequency. The CSD function outputs peak values when the cyclic frequency is equal to the fundamental frequencies of transmitted signal $x(n)$. Cyclic frequencies can be assumed to be known [95], [99] or they can be extracted and used as features for identifying transmitted signals [98].

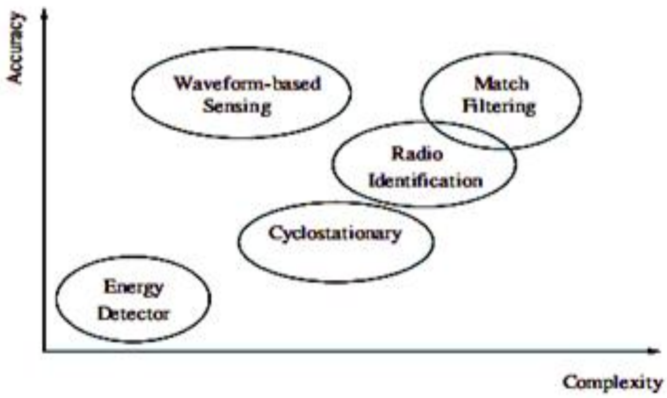

Fig. 8 Main sensing methods in terms of their sensing accuracy and complexities

A critical comparison is also provided which compares the complexity of each of the energy sensing techniques.

VIII. Applications And Research In Cognitive Radio

Cognitive Radio as a fast emerging adaptive technology is no longer merely a concept of white space utilization in the allotted spectrum space but it is finding application in several areas such as grid communication, machine to machine communication, device to device communication, in cloud computing, military applications, medical science to name a few. This section reviews most of the literature proposing sophisticated changes in such systems with the use of cognitive radio technology. Cognitive Radio technology finds use in DSA and in implementing cognitive radio networks. The major applications included smart grid communications, public safety communications, and broadband cellular to medical application. One of the very promising applications of CR will be its use in the multi-tier networks such as the two-tier macrocell-femtocell networks to improve the indoor coverage as well as the capacity of traditional cellular wireless networks. The work in [58] introduced an interesting idea of ultra-broadband femtocells based on the CR concept.

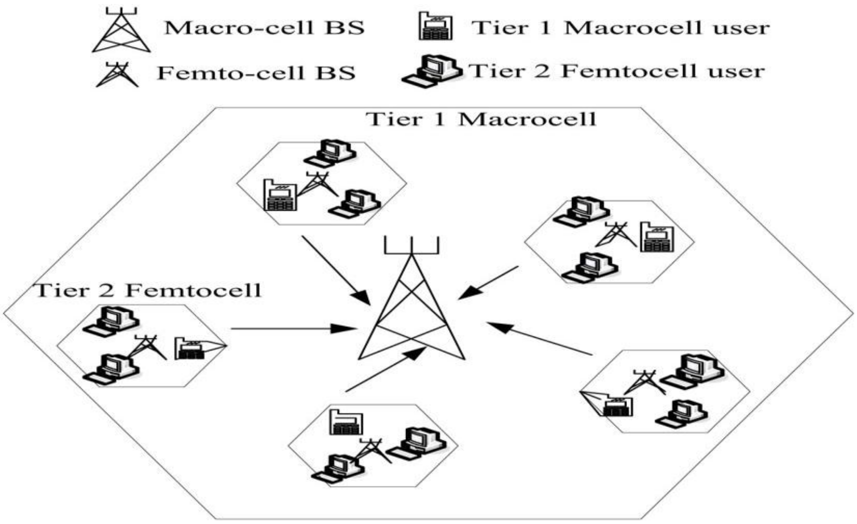

Fig. 9 Two-tier femtocell architecture

Cognitive Radio technology is also used Dynamic spectrum access (DSA) is identified as an important [Future Directions in Cognitive Radio Network Research] near-term opportunity for efficient spectrum usage and introduction of new wireless services. In [59], a cluster-based dynamic channel allocation framework is proposed for cognitive wireless mesh networks taking the issues of interference and coexistence with primary users into account. In [60], the authors presented applications of CR in the context of green communications. Cognitive radio networks can be developed to exploit the TVWS for broadband wireless access, as the analog TV bands, which are largely underutilized, have been released for data communications. Many studies in the literature considered CR on the TVWS (e.g., [61–64]). Kawade and Nekovee [65] presented the feasibility study of using TVWS for wireless home networks. Wireless technologies will be used for the smart grid communications [69]. CR is a potential solution for machine to machine communications for data transmission from a licensed channel to an unlicensed one. However this attempt might make several issues crop up. M2M communications will be application centric, in which the protocol design and optimization must take the requirements of the specific applications into account. For example, Vo et al. [70] considered M2M communications for the smart grid applications focusing on the energy consumption of data transmission through CRNs CR will be a potential technology to improve the spectrum utilization and transmission efficiency of wireless communications used in the smart grid [66-68]. Also, the performance was compared with that of 2.4-and5-GHz ISM bands, which are currently widely used. The effectiveness of cognitive radio technology can be enhanced by improving on energy efficiency. Many potential and emerging indoor applications require a dense WSNs environment to achieve an adequate QoS. Conventional WSNs experience significant challenges in achieving reliable communication because ISM bands in indoor areas are extremely crowded. Some examples of the indoor applications of WSNs are intelligent buildings, home monitoring systems, factory automation, personal entertainment, etc. CR-WSNs can mitigate the challenges faced by conventional indoor WSNs applications.

In [70] Yu and Chen studied the CRN tomography and spectrum map for cooperative spectrum sensing. A two-step cooperative learning algorithm was proposed to analyze the spatial correlation of the results from sensing nodes thus making an efficient spectrum map. The proposed algorithm is suitable for large-scale, dynamic, and heterogeneous M2M networks. M2M communications can be integrated into the existing wireless systems (e.g., WiMAX and LTE [72] networks). However, optimal system architectures must be developed for integrating M2M communications and CR into such wireless systems. With the developing trends of device-to device (D2D) communications in the limited cellular radio spectrum, CR-based avant-garde interference control and avoidance methods will be efficient and helpful for such systems. In [74], cloud computing was used as the central communication and optimization infrastructure for a CRN. This network is used for advanced metering infrastructure (AMI) to support the smart grid applications. In this case, the data processing of AMI is performed by servers in the cloud. In [75], cooperative spectrum sensing and radio resource scheduling for CR communications in the TVWS was implemented and executed in a cloud computing environment. In particular, the spectrum sensing reports ere analyzed in the CR cloud to identify the spectrum opportunities. In [76], the authors modeled a prototype system of a CR architecture implemented using cloud computing to store and process spectrum sensing data. Cooperative spectrum sensing and radio resource scheduling for CR communications in the TVWS was implemented and executed in a cloud computing environment. Cognitive radio can be a very vital solution to handling medical telemetry. Medical telemetry involves transmitting patient's vital signals over a wireless system to the monitor. In 2000, FCC had allocated 14 MHZ of spectrum as Wireless Medical Telemetry Service Band. However there are several drawbacks of WMTS, because of the allowance no multimedia streaming is allowed in the WMTS band. It is shared with utility telemetry companies and the military/governmental installations in the US on the L-band. The Channel can still be potentially interfered by TV Channel of proximity and no channelization is defined for this band.

No standard has been developed for sharing, interference management and thus the usage is inefficient. Cognitive radio poses as a solution to this.

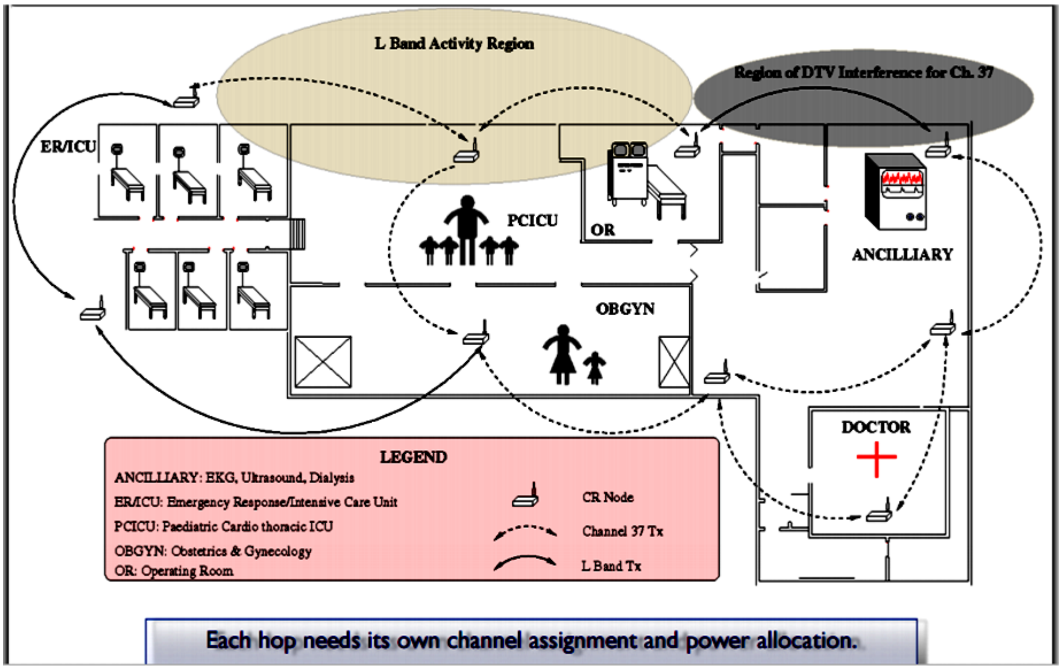

Fig. 10 CR enabled WMTS architecture.

The author in [77] also discusses cognitive radio as a solution for aiding vehicular emergency networks.FCC has allocated 75 MHz of spectrum at 5.9 GHz for Dedicated Short Range Communications. (DSRC), IEEE 802.11 p and IEEE I609.4 help in regulatory services. But the allocated band may prove to be inefficient during peak hours of traffic, e safety applications, high bandwidth entertainment etc. Utilizing the white spaces within the spectrum space with an adaptive intelligent technology like cognitive radio is a good solution. In [78] a cognitive radio is essentially considered the primary facilitator to establish an integrated and predictable coexistence management for heterogeneous wireless solutions, allowing mixed operation of cognitive and non cognitive systems simultaneously. Generic system concepts for information acquisition and rating, as well as cognitive coexistence management for wireless automation in industrial scenarios have also been considered.

DSA is currently an active field (as evidenced by the recent formation of a major IEEE conference called DySpan) and involves both technology and policy considerations. There are many important research issues in DSA including spectrum management policy, market economics, spectrum co-existence algorithms and protocols, and enabling radio technologies. The second and longer term opportunity is that of cognitive radio networks (CRNs), a term that refers to adaptive and self-organizing radio networks that are capable of responding to environmental changes such as interference, device density and end-user application requirements. Cognitive radio networks have several applications in military fields, in implementation of emergency networks, in leased networks; mesh network, multimedia and cellular networks.

The cognitive engine carries out these tasks by obtaining all available information from sources such as sensors, protocol layers, a policy engine, and then interprets, reasons, and makes the optimum decision to adapt. Integrated with ground radio stations and centralized management systems, the CR can dynamically use the available channels based on its actual location, environment condition, and, therefore, maximize the use of the limited spectrum. In [79],[80] this scope has been cultivated. One of the anticipated benefits of CR technology is that it will enable lower cost Internet access by reducing the substantial cost component associated with the purchase of spectrum. In a DSA based approach to spectrum management, unused spectrum could be accessed by users to enable broadband access to the Internet. By deploying smart mesh CRN systems, the network could create the backhaul necessary to reach remote rural areas. It could also be used in dense urban areas to enable efficient sharing of the scarce spectrum resource.

IX. Conclusion And Future Scope

Cognitive radio provides a cutting edge solution to the problem of spectrum crunch and represents a new paradigm for designing intelligent wireless networks to mitigate the spectrum scarcity problem and provide significant gain in spectrum efficiency. We anticipate that cognitive radio technology will soon emerge from early stage laboratory trials and vertical applications with regard to a theoretical approach and emerge as a multi-purpose spectrum stretching programmable radio that will serve as a universal platform for wireless system development, much like microprocessors have served a similar role for computation. There is however a big gap between having a flexible cognitive radio, effectively a building block, and the large-scale deployment of cognitive radio networks that dynamically optimize spectrum use. Building and deploying a network of cognitive radios is a complex task. Major research themes being pursued include spectrum policy alternatives, system models, and spectrum sensing algorithms, cognitive radio architecture as software abstractions, cooperative wireless communications, DSA technology, Protocol architectures for CRNs, and algorithms for network security for CRNs etc. CRN research must be relatable to the physical world and it is more than important to test the same for real-world situations. Radios work. A CRN research program must develop the tools and techniques to easily move information from field experiments (test beds) to abstract models that confirm to real life issues and move questions from the models to experiments in the field. A range of capabilities such as a flexible physical platform that supports diverse front-ends and a range of programming tools is required. First, experimental platforms are required to gather physical world experience specific to a certain situation and gather measurements in the real world platform that deploys the cognitive radio technology. Secondly, the arrangement should allow the experiments to be repeated. Third, we need techniques to abstract field experiment measurements into simpler models. This enables us to consider larger CRN systems before extensive deployment. At the same time, we need to learn how to extract questions from current model that will aid in scaling the project to a new project with a similar approach.

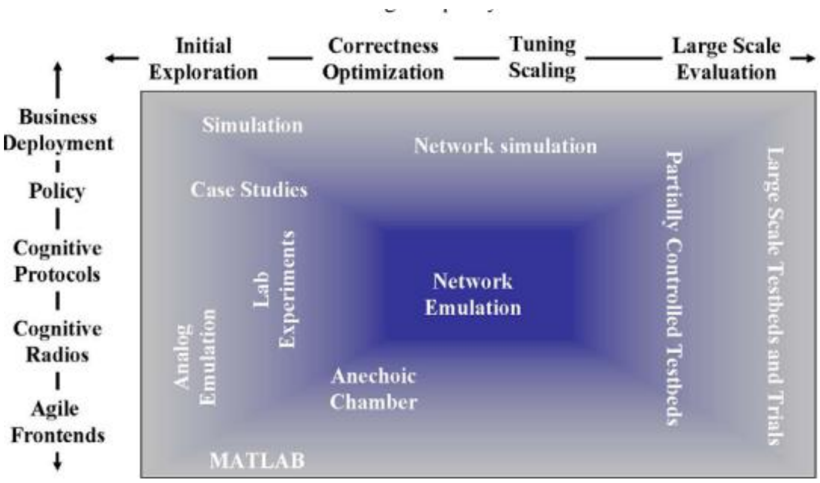

Fig.11 Evolutionary Methodology In Research concerning Cognitive Radio Technology

Huge amount of research is being carried out throughout the world with regard to this novel concept of 'spectrum stretching'. An instance of research being carried out in the labs of Nokia Research Centre may be cited. Nokia Research Centre is working on Cognitive Radio Technology to find methods for flexible spectrum use, novel ways of sensing the radio environment and location, distributed networks that cooperate intelligently and adaptively, low power flexible implementation of wireless in mobile devices. Various devices will be able to detect other radios around them and work together to optimize the use of spectrum, allocate resources and more easily communicate according to precedence if required. The research is centred in Helsinki and Otaniemi. The progress of research in this area by the Nokia Research Centre appears in several articles – on cognitive radio systems [88],[89], on cognitive radio implementation [90],[91],[92] and on optimized local access [93],[94]. The limited spectrum is allocated statically based on air traffic control organization and geographic locations. But as high complexity data applications for air-ground communications, the demand to effectively use the limited spectrum has increased. The Cognitive Radio (CR) technology allows addressing the static allocation of spectrum issue and offering a more flexible transition approach for updating the legacy air-ground radio system. The emerging CR technology provides the sensing of surrounding environment, allowing the radio to adapt to the environment accordingly. Built on software-defined radio (SDR) technology, CR is able to employ these features with the cognitive engine and the aid of several sensors. A comprehensive survey has been provided regarding the evolution of cognitive radio technology, the architecture of cognitive radio model, the implementation techniques, issues faced during experimentation, the varied and ever growing applications and some experimental references. The research activities in CR and major issues in the design of CR communication networks have been discussed (e.g., spectrum sensing, DSA, applications, and standardization), and the related work in the literature have been reviewed. First, the historical note of the CR has been given to provide a motivation of the dynamic and efficient next generation wireless systems. The various approaches of spectrum sharing in CR have been reviewed. The security and economic issues have been discussed. From the practical perspective, the reviews of simulation tools and test bed have been provided. The future trends and research directions have been discussed and open research issues have been outlined. Also, the standardization activities related to CR have been summarized.

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