Cognitive Radio: Forging ahead from Concept, Testbed to Large-Scale Deployment

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Abstract—**This article first briefly reviews the basic concepts about cognitive radio (CR) technology and CR-enabled cognitive wireless communications, and then discusses the differentiating features of CR and the fundamental theories or principles behind CR, especially from the artificial intelligence and machine learning perspective. As a CR testbed plays an important role in the transition of CR technology from concept to large-scale deployment, a survey on the state-of-the-art development on CR testbeds is presented, which indicates the trend of future development. Emerging research topics and potential applications of CR technology in various areas are also discussed which could be further investigated in an innovative CR approach.**

Index Terms—**artificial intelligence, cognitive engine, cognitive radio, cognitive wireless communications, machine learning, testbeds**

I. INTRODUCTION

Since the term "cognitive radio" (CR) was coined by Dr. Joseph Mitola III in late 1990s [1, 2], it has been gradually viewed as a new paradigm for enabling much higher spectrum utilization, providing more reliable and personal radio services, reducing harmful interference, and facilitating the interoperability or convergence of different wireless communication networks [1−5]. CRs have the potential to drive the next generation of radio devices and wireless communication systems design. Software defined radio (SDR) provides an ideal platform for the realization of CR. It is expected that CR will evolve from current SDR radio by adding more and more cognition features, such as comprehensive situation awareness and learning capability.

CR has broad impact on various application sectors such as military, public safety, and commercial communications. As a result, CR technology has been the focus of huge research and development efforts around the world in the past decade. However, CR technology is essentially in the preliminary stage, as no large-scale CR network has been deployed yet. This paper intends to present a brief overview of the development of CR technology from different perspectives, and reveal the development trends and potential applications of cognitive wireless communications.

The remaining of this paper is organized as follows. The basic CR concepts are introduced in section II; in section III, we briefly overview the principles and key technologies behind CR; in section IV, we discuss the various applications of CR technology and review the testbeds developed by the research community. In section V, the development trends and emerging research topics related to CR technology are discussed. Finally, our vision on CR is presented in section VI.

II. BASIC CONCEPTS

Due to the inter-disciplinary nature of CR research, the technical background of CR covers a wide range of areas, such as signal processing, artificial intelligence, databases, and wireless networking. Several basic concepts have been introduced for CR research, such as "cognition cycle", "spectrum hole", "cognitive engine", and "policy engine". Note that regulatory (policy) and business issues might be even more complicated as compared to the technical issues.

A. Cognition Cycle

CRs observe their operational environment and become aware of their situations, make in situ decisions according to their observations, anticipations, and experiences, and then execute intelligent adaptations to maximize their utilities subject to many constraints. They evolve by a spiral learning process, which is also known as the "cognition cycle" throughout their lifetime, as illustrated in Fig. 1. The database is at the heart of most business transaction processing systems. If we envision

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CRs' activities as "radio transactions," then it becomes apparent that databases would be at the heart of future CR networks. For a strong cognitive engine, the cognition capability relies on three types of memory (database): radio environmental information base, knowledge base, and experience base (case library), which enables CR to learn from radio environment, past experience, and knowledge, respectively.

B. Spectrum Hole

A spectrum hole (a.k.a. spectrum opportunity) refers to part of radio frequency spectrum, originally assigned to a primary user, is not being utilized by that user at a particular time, and at a specific geographic location [3]. Detecting a spectrum hole is one of the most important observation objectives for CR.

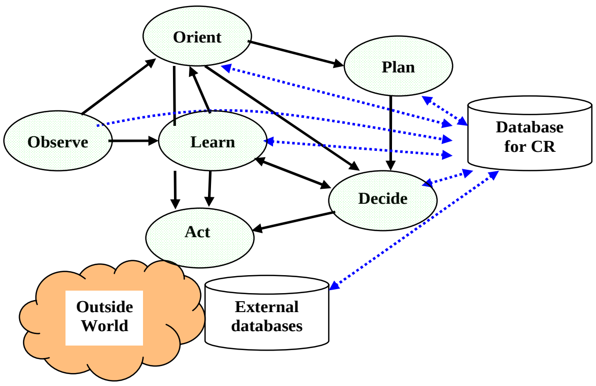

Fig. 1. Cognition Cycle and the Role of Databases for CR (adapted from [2])

C. Cognitive Engine

The cognitive engine (CE) is the "brain" or intelligent agent of a CR. The CE is essentially a software package that can make any electronically agile radio platform cognitive.

D. Policy Engine

Policy engine is a term from the U.S. DARPA next generation (XG) program [6]. The policy engine constrains the behaviors of the CR so as not to violate certain conditions such as frequency, bandwidth, and transmit power restrictions for various locations.

The XG program intends to solve two key problems, i.e., spectrum scarcity and difficulty of wireless communication systems deployment, by introducing a protocol for spectrum and policy agility. Policy agility is achieved by exchanging policies using machine-understandable policy language among XG nodes, such as Web Ontology Language (OWL). To accomplish policy agility, the XG program uses an approach that decouples policies from behaviors and behaviors from protocols [7]. Through abstraction, the XG program decouples policy, behavior, and protocol. Decoupling allows adaptation to policies that vary over time and geography. One of the benefits of decoupling is traceability, that is, the ability to associate each emission with a policy or a set of policies that permit this emission. Traceability is a valuable feature that helps to address the painful verification and validation problem.

E. Situation Awareness

Comprehensive situation awareness and learning capability are the most differentiating features of CRs. Situation awareness may include location awareness, RF environment and network topology awareness, mobility and trajectory awareness, capability awareness, context awareness, and so on. The CR can obtain situation awareness through various sensors and/or databases such as the global/local radio environment map (REM) [8, 41]. Situation awareness can also be symbolized as "X-awareness", where "X" may refer to location, energy, spectrum usage, network topology, etc.

Note that there are actually three levels of situation awareness: "perceive," "understand," and "anticipate," respectively. To explain these three levels of situation awareness; think about an insightful analogy between two intelligent agents: cognitive radio and taxi driver. For a smart taxi driver, he always looks for and perceives basic information when he drives, then thinks about and understands the meanings of that information, finally, uses the environmental understanding to anticipate what will happen ahead in time and space, and then autonomously adjust his driving operation accordingly. In addition, a smart taxi driver always learns from past experiences and prior knowledge to deal with various situations better and better. The goal is to obtain higher income while complying with safety and business regulations. Similarly, the idea is for CR to exploit its situation awareness in order to achieve its goals, such as minimizing interference or maximizing throughput, or using available spectrum holes efficiently, etc.

F. Learning and Decision Making Capability

Learning and decision making capability can be symbolized as "Self-X" where "X" may refer to configuration, optimization, adaptation, planning, maintenance, etc. Common machine learning techniques include, but are not limited to, case-based learning (CBL), knowledge-based learning (KBL), search engine-based learning (such as classical, mathematical optimization techniques, simulated annealing, evolutionary genetic algorithms (GA), ant colony optimization, and Tabu search), artificial neural networks (ANN), statistical learning such as Hidden Markov Models (HMM) and Bayesian learning, and cooperative learning [10]. Interested readers are referred to [9] for a more detailed description and comparison on these machine learning techniques for CR.

Basically, each machine learning technique has its advantages and limitations. There is no single machine learning technique effective for all kinds of CR applications. To achieve better performance, it may be preferable to leverage more than one machine learning techniques when designing a powerful cognitive engine [41].

III. FUNDAMENTAL THEORIES AND KEY TECHNOLOGIES

A. Theories or Principles

The fundamental principles behind CR, including but not limited to the following:

- *Detection and estimation theory*: detection and estimation theory is important for spectrum sensing and relevant parameters estimation (such as signal detection rate and false alarm rate) [3, 11].
- *Evidence theory*: for example, the famous Dempster–Shafer theory, a mathematical theory of evidence, can be employed to combine evidence from different sources and arrive at a degree of belief.
- *Game theory*: used as an important tool in studying, modeling, and analyzing the behavior and interactions of cognitive nodes [12, 13].
- *Information theory*: information theory is important for investigating or understanding the capacity limit of CR networks.
- *Elements of wireless communications and networking*: such as the radio channel models and wireless ad hoc network routing protocols.

B. Artificial Intelligence

Artificial intelligence (AI) is one of the key technologies in CE design. AI means the simulation of human behavior and cognitive processes on a computer. The ability to learn or adapt one's behavior to a new situation is a vital component of intelligence. The fundamental issues of AI involve knowledge representation, search, perception, and inference. Knowledge can be available as collections of logical assertions, heuristic rules, procedures, statistical correlations, etc. Organizing knowledge is an important issue in the learning process. Knowledge also includes a framework in which the various facts and aspects of experience can be stored [10]. Searching techniques are very important, which can help to avoid the combinatorial explosion problem encountered by brute force attempts. Inference is the process of creating explicit representations of knowledge from implicit ones, which can be viewed as the creation of knowledge itself. A number of techniques that are currently popular within the area of applied AI include expert systems, fuzzy systems, neural networks, genetic algorithms, swarm intelligence, and (soft) case-based reasoning [10].

It is evident that many research efforts have been devoted to designing CEs for various CR applications. The successful development of CEs is a crucial aspect for the implementation of CR. For example, Virginia Tech researchers developed a biologically inspired CE based on genetic algorithms. The CE is capable of learning and intelligently evolving a radio's PHY and MAC layers when faced with unanticipated wireless and network situations [14]. Virginia Tech researchers also developed a CE based on a knowledge-based reasoner and a genetic algorithm multi-objective optimizer [18, 34]. This hybrid CE adopts a modular approach, thus the reasoner and optimizer modules could be used at any time during the algorithm adaptation procedure. One of the main advantages of this approach was that adaptation time decreased when the CE used knowledge to limit the search space of the GA optimizer [35].

Stuntebeck proposed a generic architecture for an open source CR, dubbed OSCR [19]. OSCR facilitated the integration of a CE with one or more SCA based radios using Virginia Tech's SCA's implementation Open Source SCA Implementation-Embedded (OSSIE) [17]. The CE was implemented using the Soar concept [20]. Soar is a general cognitive architecture for developing systems that exhibit intelligent behavior. The authors followed with an implementation of the CE and its application in two cases: maximizing capacity in an AWGN channel and in a non-AWGN channel [21]. Newman presented a genetic algorithm (GA) driven, CR decision engine that determines the optimal radio transmission parameters for single and multi-carrier systems. In their research, the authors also illustrated the trade-off between the convergence time of the GA and the size of the GA search space [23]. Baldo and Zorzi proposed the use of Fuzzy Decision theory for cognitive network access decision-making [24, 25].

C. An Approach to Machine Learning in CR

Machine learning, as explained by Dietterich and Langley, tries to understand the computational mechanisms by which experience can lead to improved performance [46]. In other words, we say that "learning" has occurred if the system can perform an action that couldn't performed, or couldn't performed as well, before that experience. Langley and Simon [47] found that the application of learning methods followed a specific pattern as described in the following steps: *formulate the problem, determine the representation, collect training data, evaluate the learned knowledge, and lastly fielding the knowledge base in order to determine what is the best way to use it*. Furthermore, there are several agreements [46] in the machine learning discipline that help us narrow the approach: *experiments have shown that there is no mechanism that leads to better learning, representational issues are integral to achieve the learning and learning occurs in the context of a performance task*. Considering these general agreements, we must focus on how to formulate the problem, how to represent the data, and how to define the desired performance task in order to facilitate learning for CR.

There are three general problem formulations for learning in the context of a performance task: classification and regression, acting and planning, and interpretation and understanding. Figure 2 summarizes how these formulations are related. If we focus on these three formulations we can get a clearer idea on the representation of the data and the desired performance task.

The first formulation focuses on learning knowledge for the performance task of classification and regression. An example, of the first formulation in wireless networks is classifying and predicting the coverage area of base station, based on the number of dropped calls observed in the training data. There are two performance tasks in the example: one to classify the coverage area, the second to predict if the call will be dropped or not. In this case, the problem has been formulated as a classification and regression problem. The data is represented in cases, and the most important features (i.e. location of the node, received signal strength, velocity, etc.) of these cases have been extracted. Classification and regression is the simplest formulation for a learning problem.

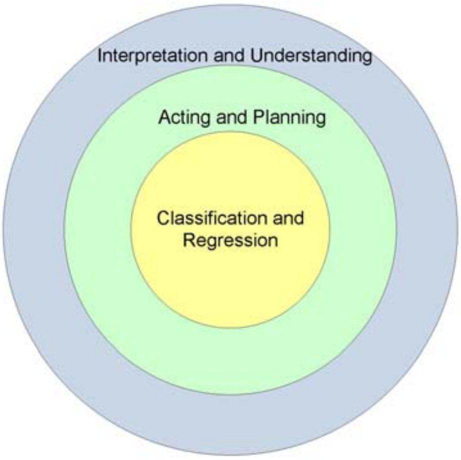

Figure 2: Machine Learning Formulations [45].

The second formulation focuses on learning for selecting actions or plans for an agent [46] The process involves making cognitive choices about future actions. This formulation usually employs a search through a space of possible outcomes, which can be constrained by the use of knowledge. An example of this type of formulation in wireless networks; is for the cognitive radio to plan for the lack in coverage, and decrease the probability of dropped calls in a specific area of the base station, by modifying its actions such as increasing power, handing over to another cell or to another system (i.e. Wi-Fi). This formulation can also be simplified to the first formulation if the actions and plans are determined in a reactive way, ignoring past information. The third formulation addresses learning via interpreting and understanding the situation. In this formulation the models and the data are contained in deeper structures, this process is often referred as *abduction*. One example where this formulation is used extensively is in natural language processing. The performance task in this case involves parsing sentences using a context-free grammar [46]. For a cognitive radio, the performance task can be interpreting that the coverage gap in the base station is due to an obstruction, given the pattern of the dropped calls. This is something that a human can interpret easily just looking at the coverage map, the idea is for the cognitive radio to interpret and understand the coverage situation without the need of human interpretation. The cognitive radio uses past experience, and the reported dropped calls from the mobile node to interpret and understand the coverage problem. This is Mitola's vision of a cognitive radio.

IV. Applications and Testbeds

A. Applications of CR Technologies

CR is a promising approach for wireless operators and manufacturers to achieve their network evolution goals. What is uncertain at this point is the cost of applying CR to wireless networks, the adoption of CR as a secondary user and coexistence with the current (legacy) network architectures is probably the least disruptive approach. CR can improve system coverage by allowing communications between heterogeneous networks, also at the user level CR can exploit past information and current spectrum measurements to prevent coverage problems. CR can increase system capacity by managing the spectrum more efficiently and using non-contiguous bands of frequency. CR can also increase end-user data rates by providing broader frequency bands, either by underlaying techniques in the current spectrum or by using non-contiguous bands.

Spectrum management is probably the most useful application for CR. However, applying cognition to radio resource management methods can bring significant network performance improvements. Also, this application of CR does not depend on approval of regulatory agencies. Therefore, it is a more attractive commercial application. Some of the possible radio resource management applications for CR technology include, but are not limited to, the following:

- Scheduling: CR can optimize packet scheduling based on the types of wireless networks service or based on service differentiation.
- Handover management: CR can anticipate when a handover is needed using past experienced.
- Fault detection and prevention: CR can exploit previous data in the network’s fault log and use them to tune the network.
- Mode/service selection: the CE changes from radio access network (i.e. GPRS, GSM, WCDMA) depending on the application requirements and the available connection.
- Power amplifier optimization: the CE reduces peak-to-average radio through power control, scheduling and handover.
- Interference management in small cells: CR can improve co-existence with the cellular infrastructure by providing scheduling and channel allocations.
- Planning tool for layout: the CE determines ways to incorporate past experience into cellular layout and tuning tools.

Furthermore, focusing on the current engineering challenges, CR has been identified as an enabling technology for four emerging technologies: the smart grid, wireless eHealth networks, public safety cognitive networks and green communication networks.

B. CR Testbed Development

An integral part of CR technology deployment is the validation of the CE algorithms. Until recently, most of the validation was performed via simulation due to the complex nature of the networks and testing scenarios. However, experimentally driven research is needed in order to leap from the theoretical analysis and simulation to actual implementations and final adoption of CR technology.

A typical CR node consists of three components: the RF front end, reconfigurable hardware and the software platform. Typically CR nodes are constructed using off-the-shelf components. Three often-used solutions are the Universal Software Radio Peripheral (USRP) platform made by Ettus Research [26], the Wireless Open Access Research platform (WARP) from Rice University [27], and the Software Radio (Sora) platform developed by *Microsoft Research* [39].

WARP consists of four key components: custom hardware, platform support packages, open access repository, and research applications [42]. It utilizes Xilinx Virtex-II Pro FPGA as its baseband processor and up to 4×4 MIMO system can be built. The physical layer functionality is designed by the FPGA logical programming language or MATLAB, while the MAC layer functionality is designed using C programming on the embedded PowerPC processor. The platform is supported by the VHDL and the MATLAB toolbox in the Xilinx.

Sora operates on commonly used *Microsoft* Windows XP system. It combines the performance and fidelity of hardware SDR platforms with the programmability and flexibility of general-purpose processor (GPP) SDR platform. Sora employs the advanced computer technologies such as multi-core architecture, look-up tables, SIMD (single instruction, multiple data), and core dedication to meet the challenges of high throughput and low latency. The maximum sample data rate is up to 16.7 Gbps with PCI-Express data bus.

In recent years, several large-scale CR testbeds have been deployed in the US and in Europe. These CR testbeds are generally constructed with off-the-shelf equipment similar to one described in the previous section. We briefly describe the research focus of each testbed as follows:

(1) CREW (Cognitive Radio Experimentation World)

CREW is an European Union Framework Programme 7 (FP7) project, which aims to establish an open federated test platform, which facilitates experimentally-driven research on advanced spectrum sensing, cognitive radio and cognitive networking strategies in view of horizontal and vertical spectrum sharing in licensed and unlicensed bands [32]. As shown in Fig. 3, this testbed has incorporated five individual wireless testbeds incorporating diverse wireless technologies (heterogeneous ISM, heterogeneous licensed, cellular, wireless sensor, heterogeneous outdoor) augmented with state-of-the-art cognitive sensing platforms. CREW also supports open access for external peer researchers.

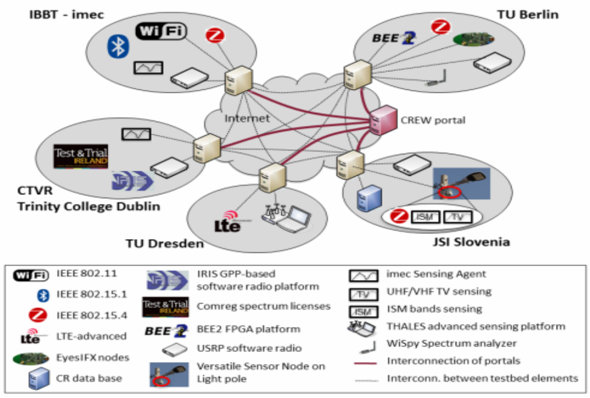

Fig. 3: Illustration of the European Union CREW Testbeds [32]

(2) CORNET (Cognitive Radio Network Testbed)

CORNET is a heterogeneous wireless network testbed based on CR technology developed by Virginia Tech. The network consists of 48 nodes located in the ceiling throughout the newly built building. Each node has two distinct parts, one is based on the Intel Xeon processor GPP platform, and the other is USRP2 (VirtexSpartan3 FPGA) as the RF front-end. Gigabit Ethernet is used as the bus connection between a general-purpose processor and the USRP2. Each node can use open source software radio platform (GNU Radio or OSSIE) as the actual signal processing components. The testbed focuses on CE design, self-organizing networks, and topology research. The testbed employs USRP2 platforms along with a custom made daughterboards [29]. In addition to the static 48 nodes deployed in the ceiling, low-power mobile nodes will also be available in order to provide a research environment that accommodates a wide variety of research topics. Note that CORNET is also openly available for performing research on advanced CR Networks. CORNET provides a unique collection of resources to researchers who don't have the ability to perform advanced experiments due to limited exposure to software defined radio and CR platforms.

(3) ORBIT Wireless Network Testbed

ORBIT has been developed and operated by Rutgers WINLAB, consisting of four hundred 802.11 radio nodes. The testbed is a two-tier laboratory emulator/field trial network [22, 30]. The ORBIT project was started in September 2003, with the objective of developing a large-scale open-access wireless networking testbed available to the research community working on next-generation protocols, middleware and applications. The project is currently continuing, which supports operations and several key technical upgrades including the introduction of software-defined radio capabilities. The ORBIT project is closely aligned with the GENI (global environment for network innovation) experimental network deployment and serves as a proof-of-concept experimental platform for wireless aspects of the program. In the longer term, campus-wide network testbeds like ORBIT can be used to for trial deployment of new mobile/wireless services and software [30].

The ORBIT testbed is centered on the "radio grid emulator" which provides facilities for reproducible networking experiments with large numbers of wireless nodes. The testbed also includes an outdoors "field trial system" intended to support real-world evaluation for protocols validated on the emulator, and for application development involving mobile end-users. Note that researchers can access the ORBIT radio grid via an Internet portal, and the portal provides a variety of services to assist users with setting up a network topology, programming the radio nodes, executing the experimental code, and collecting measurements [30]. Upgrade of the testbed with GNU/URSP2 radios to support programmability at the radio PHY and MAC layers has recently been completed (with 28 USRP and USRP2 radios installed in the first phase), with the objective of support CR networking experiments [30]. The main ORBIT radio grid and outdoor testbeds have been further supplemented with a number of experimental "sandboxes" which allow researchers to debug and test their code without tying up the resources of the larger radio grid; Currently available sandboxes include Wi-Fi, WiMAX, OpenFlow and GNU/USRP [30].

(4) Emulab

Emulab is a network emulation testbed developed by the University of Utah [31]. Emulab is a network testbed, giving researchers a wide range of environments in which to develop, debug, and evaluate their systems. The name Emulab refers both to a facility and to a software system. The Flux Group from the School of Computing at the University of Utah oversees the primary Emulab installation. There are also installations of the Emulab software at more than two-dozen sites around the world, ranging from testbeds with a handful of nodes up to testbeds with hundreds of nodes. Emulab is widely used by computer science researchers in the fields of networking and distributed systems. It is also designed to support education, and has been used to teach classes in those fields. Emulab is a public facility, which is open to most researchers worldwide.

(5) CORAL (Cognitive Radio Networking Solution)

CORAL is a Wi-Fi-based CR networking system that has been developed at the Communication Research Centre in Canada [43]. The commercial release is in November 2010 and it is claimed as the first commercially available Wi-Fi cognitive networking system. The CORAL system was designed specifically as a research network that universities and labs can use in a live Wi-Fi network to research and experiment with CR networking. The key features of CORAL Wi-Fi CR network is as follows [43]:

- A self-contained Wi-Fi network that has CR capabilities built into the architecture and components.
- Fully configurable as each node is configured from the Network Management system.
- Open and programmable: APIs allow the user to develop and implement cognitive engines to drive the network.
- 802.11 compliant and operates in the ISM 2.4 GHz band.
- Deployable in different network architectures such a mesh, point to multi-point and relay networks.
- Designed to support various antenna types to enable experimentation with steerable antennas.
- A tool that can be used to collect data and develop a Radio Environment Awareness Map for a given area.
- Expandable from a small lab bench network to a regional or campus wide operational Wi-Fi network with interference mitigation and network performance optimization capabilities.

In sum, CORAL allows researchers to investigate fresh approaches to broadband wireless networking, giving them the opportunity to implement CR functionality that has only been simulated or discussed in theory. CORAL's design was driven by concepts proposed at the ITU and by standards bodies such as IEEE 802.16, 802.11 and 802.22 [43].

V. Trends and Emerging Applications of CR

A. *Development Trends of CR*

Recently, CR technologies have been gradually adopted by communication standards as the enabling technology. For example, IEEE 802.22 WRAN is the first commercial application of CR networks re-farming the TV broadcast bands. The IMT-Advanced (4G) mobile communication systems, which are still under standardization process, also require CR technologies (such as non-contiguous spectrum access) to support opportunistic and spontaneous communications.

In addition, we observe the following trends for recent CR research and development:

- The CR testbed has been developed from a stand-alone proprietary system to a federated or an open access system.
- From node-level cognition to network-level cognition: e.g., the cognitive cloud can leverage the cloud computing technology to shift the computational load from the CR node to the network (cloud).
- From dedicated systems to heterogeneous systems: the application of CR has been extended from dedicated systems to heterogeneous systems. In the future, each type of wireless networks will exhibit CR behavior.
- From lower layers to higher layer cognition with cross-layer optimization: e.g., CR technology is employed for context-aware streaming videos transmission [38].
- From macro-scale cognition to micro-scale cognition: cognitive electronic devices are under development with the advancement of nanotechnology and MEMS.

B. Emerging Research and Application Areas

CR technology is especially needed in face of spectrum shortage, supporting agile and flexible waveforms for challenging application scenarios. After ten years' development, the research areas of CR have been extended significantly from the originally focused area (i.e., dynamic spectrum access) to much wider areas. Emerging research or potential application areas include, but are not limited to, the following:

- Applying CR technology to green communications by leveraging CR technology for power efficiency of communication networks.

- Applying CR technology to IMT-Advanced and beyond: cognitive MIMO, carrier aggregation, and heterogeneous network support, self-planning and self-organization through collaborative CRs, supporting device-to-device (D2D) communications with a CR approach so as to mitigate or avoid interference.

- Applying CR technology to high-speed rail broadband wireless communications: for example, a CR approach can be employed to deal with the various challenging issues for broadband wireless communications between the high-speed train and the track-side base stations, such as fast channel estimation and adaptation, significant Doppler spread and the associated inter-carrier interference (ICI), signaling storm and fatal communication disruption resulting from frequent group handover, coexistence and spectrum management issues with existing wireless systems. Fig. 4 illustrate the system architecture of a cognitive broadband wireless communication system for high-speed railway or subway, in which the cognitive engine is designed to obtain radio channel condition awareness and make timely adaptations along a given route.

- Applying CR technology to internet of things (IOT), which could help avoid the RF tag pollution problem.

- Applying CR technology to cognitive wireless sensor networks, featuring spectrum-awareness, energy-awareness and self-organization capabilities.

- Applying CR technology to eHealth: exploiting CR technologies to limit interference to biomedical devices and equipment while transmitting patient data safely and securely.

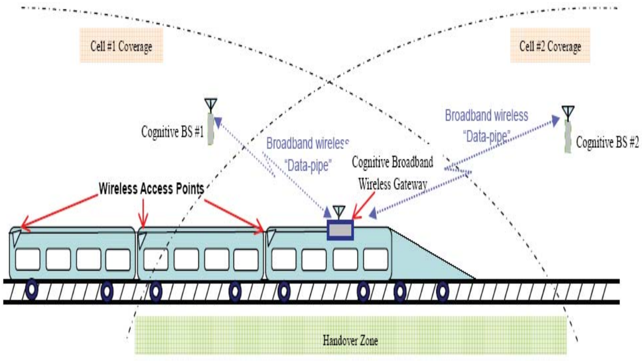

Fig. 4: Illustration of Cognitive Wireless Railway Communications between a Train-top Wireless Gateway and Track-side Base Stations Supporting Multi-mode, Multi-band Broadband Wireless Communications

- Applying CR technology to wireless communications in unknown space (e.g., exploration of the moon or Mars with robots equipped with cognitive radios).

Interested readers are referred to a recent paper [44] for more detailed discussions on the emerging applications of cognitive wireless communications, ranging from smart grid, public safety, broadband cellular, to medical applications.

C. From Concept to Practice: CR Implementation

Two practical approaches to developing CR are identified and briefly discussed as follows:

(1) Low-Complexity CE Approach

The advantage of this approach is to find a cost-efficient approach to developing CR and quantifying its performance. An integrated database, REM (radio environment map), is proposed as the navigator for CR [33−37]. The REM includes multi-domain information such as RF and geographical environment information and prior knowledge. The vision is that future CR will have REM inside and may access the built-in local REM as well as the global REM maintained by the CR networks. Through APIs, the CE can "Google" the REM for comprehensive situation awareness, efficient learning, and fast adaptation. For example, the 802.22 WRAN BS CE adapts much faster when using the CKL algorithm than when using the GA, especially under complicated situations. Fast adaptation is critical for time-sensitive WRAN applications, such as evacuating a TV channel for primary users [37].

(2) High-Performance Computing Approach

This approach employs parallel computing by taking advantage of multi-core CPU or resorting to cognitive cloud computing which shifts the computation load (e.g., sophisticated CR algorithms) to cloud computing from a CR node. This is another way for practical CR implementation. Cloud computing can be viewed as a service for CE.

In addition, huge standardization (such as IEEE 802.22, IEEE 802.16h, CogNeA Ecma TV white space standard) and regulation efforts also help to facilitate large-scale deployment of CR networks in a cost-efficient way [44].

C. Case Studies

In this section we present two case studies that show how CR can improve performance in wireless communications networks. *Case Study 1* focuses on a REM-enabled CE for 802.22 WRAN, while *Case Study 2* focuses on a Decision Tree Learning (DTL) CE for handover management in 3G networks.

(1) REM-enabled CE for 802.22 WRAN

The radio environment map (REM)-enabled CE has been developed for 802.22 WRAN, which presents a cost-effective approach to developing CRs [33−38, and the references therein]. As shown in Fig. 5, the cognitive WRAN base station (BS) could consist of a spectrum-sensing module, REM, CE, and (software-defined) radio transceiver. The CE may have case- and knowledge-based learning (CKL) modules, a channel modeler and predictor, a multi-objective optimizer, a spectrum manager and other functional entities. The CE first obtains situation awareness by querying the REM, and then determines the utility function that best fits its current situation. Note that the multi-objective optimizer helps the CE to reach multiple goals, such as minimizing harmful interference and maximizing spectrum efficiency [35].

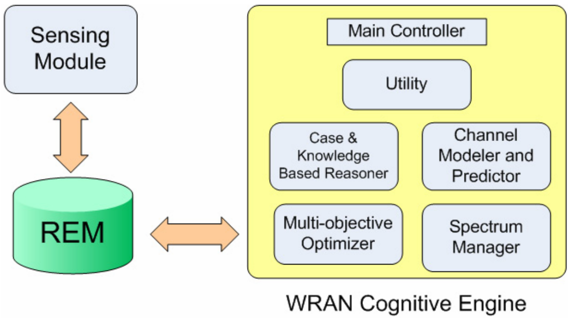

Fig. 5: Block Diagram of REM-based CE for 802.22 WRAN BS [35]

(2) Decision Tree Learning CE for Handover Management

A DTL CE has been developed for 3G wireless networks, including a low-complexity engine that resides in the Node B is a less disruptive approach to adding cognition to wireless networks [40, and the references therein], especially if cognition has not been planned for in the original network design. As shown in Fig. 6, the CE for 3G networks could consist of a "spectrum sensing" module, a REM, an Environment Analyzer, and a core agent located in the Radio Network Controller (RNC). The CE is the core agent and includes a reasoning module, a learning module, and an optimization module. The cognitive engine has been designed using DTL in order to minimize computational complexity.

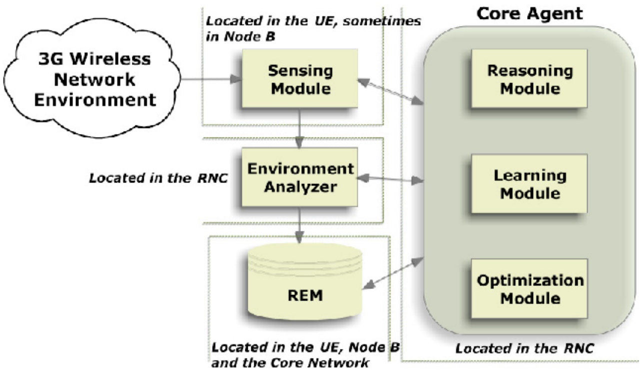

Fig. 6: Block Diagram of REM-enabled Decision Tree Learning CE for Handover Management in 3G Networks [40]

E. CR Deployment Issues

Performance evaluation of CR networks is an important and challenging technical issue. For CR, the cognition capability relies on dynamically choosing the proper performance metrics and updating utility functions for decision making and learning. Traditional wireless network simulation or testing tools are mainly focused on lower layers. It is critical to incorporate faithful PHY models into these tools without greatly increasing the code complexity and simulation execution time [37]. How to effectively yet trustfully validate a CR device under varying known or even unknown scenarios is an open issue to address.

It is likely to evaluate the cognitive functionality of CR with "IQ" and "EQ" as employed for human beings. The "IQ" indicates the level of intelligence for a single CR node, whereas the "EQ" indicates the capability of cross-node (or cross-network) collaborations of the CR device, e.g., the capability of obtaining (global) environmental awareness through collaborative sensing with other nodes (or through network infrastructure) [37, 41].

Furthermore, non-technical issues, such as policy issues and feasible business models, are even more difficult to tackle with for large-scale deployment of CR networks.

VI. CONCLUDING REMARKS

CR technology is an emerging research area that requires interdisciplinary collaboration. CR is both a revolutionary technology and an evolutionary technology. On one hand, from the concept perspective, a variety of paradigm shifts in wireless communications are expected with the introduction of CR: shifting from static spectrum allocation to dynamic spectrum access and sharing; and from predefined behavior and limited adaptation capability to flexibility and intelligence to deal with unpredictable demanding scenarios. It will also drive the next generation of radio devices, communication systems design and testing tools. On the other hand, from the real-world CR deployment viewpoint, it is evolutionary and will evolve from the current SDR.

CR changes the way in which we view, design, test, certify, and operate the radio. Future CR will have cognition and intelligence at all levels: from physical layer up to application layer; from baseband signal processing up to RF transceiver and antenna systems; and from a single node to whole communication networks. Many open research issues (such as CR-related security issues, validation issues, and policy issues) remain to be investigated in order to unlock the expected potential of CRs.

Though CR technology is still in the preliminary development stage, large-scale CR deployment in various application areas are emerging quickly along with the reforms of spectrum policy or regulations, and the advancement of micro-electronics, high performance computing, machine learning, among many other technologies.

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