Cognitive Radio Networks

Adrian Popescu

Dept. of Communications and Computer Systems
School of Computing
Blekinge Institute of Technology
371 79 Karlskrona, Sweden

***Abstract*—**
Cognitive Radio Networks (CRNs) are emerging as a solution to increase the spectrum utilization by using unused or less used spectrum in radio environments. The basic idea is to allow unlicensed users access to licensed spectrum, under the condition that the interference perceived by the licensed users is minimal. New communication and networking technologies need to be developed, to allow the use of the spectrum in a more efficient way and to increase the spectrum utilization. This means that a number of technical challenges must be solved for this technique to get acceptance. The most important issues are regarding Dynamic Spectrum Access (DSA), architectural issues (with focus on network reconfigurability), deployment of smaller cells and security.

I. Introduction

Current networking technology is generally limited with reference to network's ability to adapt to diverse changing conditions, which may result in sub-optimal performance. Another serious problem is because of the existing rigid spectrum allocation, with the consequence of resource wastage and limited business models. With few exceptions, the network elements are today limited in scope, state and response facilities. This means that they are unable to take intelligent decisions. The existent adaptation mechanisms are typically reactive, they only react after a problem occurs. This largerly limits the network ability to provide intelligent and efficient solutions, also with reference to green networking and advantageous business models.

Cognitive Radio Networks (CRNs) provide the increase of spectrum utilization by using unused or less used spectrum. Unlicensed users have access to licensed spectrum, under the condition that the interference perceived by the licensed users is minimal. This means that there is need not only for new communication and networking technologies able to use the spectrum more efficiently (in terms of, e.g., increased bit/s/Hz/cell), but also for new advanced techniques to increase the spectrum utilization. This opens up for a number of technical challenges that must be solved for this technique to get acceptance.

Fundamentally, CRNs are based on using Cognitive Radio Devices (CRDs) able to configure different parameters on the fly (e.g., frequency band, waverform, transmit power), depending upon the surrounding environment and consequently exploiting under-utilized spectrum portions and avoiding annoying bottlenecks. A so-called Cognitive Process (CP) is used for purposes like collecting relevant information, machine-learning and, based on that, reasoning and decision-making. Configurable radio platforms like Software Defined Radio (SDR) can be used to execute the decisions of CP. Ideally, such a system should be able to take predictive actions as well.

Cognitive radio technology is a key concept suggested to be part of the so-called 5G, the 5th generation mobile networks. 5G is currently not an official term used by standardization bodies or telecommunication companies. It is rather considered to be a term that covers the challenges that 4G would present when it enters widespread use.

Given that 3G Long Term Evolution (LTE) pilots are already up and 4G Long Term Evolution - Advanced (LTE-A) pilots are expected around 2015, and also based on the general belief that each generation of wireless systems takes about a decade, that means 5G pilots are expected around 2025. Today, it seems to be likely that 5G will not consider faster bearer than 4G, but rather focus on architectural and networking aspects. Key 5G features are expected to include, among others, pervasive wireless computing and communications, cognitive radio technology, IPv6, wearable devices with Artificial Intelligence (AI) facilities, unified global standard. Protocols like Wi-Fi and Bluetooth are expected to be available as radio applets by 2020, leading so to new technological breakthroughs as well as new opportunities.

The rest of the paper is as follows. Section II is about the basic concept of cognitive radio, also complemented with a short presentation of the basic operations. Section III is about spectrum management in CRNs. Section IV is about heterogeneous networks, which is how the future wireless networks will look like. This largerly influences the architecture and control elements of CRNs. Based on that, a short presentation of the CRN control elements and architectures is done in Section V. Section VI is about Dynamic Spectrum Access (DSA). Security issues are considered in Section VII. Finally, the paper is concluded in Section VIII.

II. Basic Concepts

The term "cognitive radio" was first defined by Joseph Mitola in his PhD thesis at Royal Institute of Technology, Stockholm, Sweden [1]. It is important to point out the difference between the terms Software Defined Radio (SDR) and cognitive radio. SDR is a radio set where most of radio and intermediate frequency functionality is done in digital form, to compare with classical radio technology. By this, SDR allows for more flexibility in radio operation. On the other hand, Cognitive Radio (CR) is about the control entity that helps SDR to determine the operation mode as well as the particular parameters to use in the particular networking situation.

A Cognitive Radio Network (CRN) is defined to be a network that is controlled by a so-called Cognitive Process (CP). This is an entity that continuously senses and collects context information about the radio environment, processes it and, based on that, it takes a decision regarding appropriate actions for the particular situation. The decision is also considering the selected profile input and the set of policies available, to be followed in the particular context.

These actions may refer to diverse optimization algorithms used in different layers in the TCP/IP protocol stack, e.g., MAC layer (selection of Radio Access Technology, frequency band, transmission power, modulation scheme). For the IP layer, these decisions refer to routing, which is expected to be of type multi-dimensional ad-hoc. By "multi-dimensional" it is meant that the end-to-end (e2e) route is expected to pass through several dimensions like, e.g., space, frequency, power, time.

CP can be implemented in a centralized or distributed way, each of them with associated advantages and drawbacks [2]. It is important to mention that both Cognitive Radio Devices (CRD) and CRN share the same CP, although they differ in algorithms and tasks.

Basically, a high-level model, the so-called Observe, Orient, Decide and Act (OODA) loop is used for CP [2]. This loop is focused on the following tasks:

- Observe the radio environment
- Learning, to adapt to previous mistakes
- Orient the adaptation process
- Decide on a particular action
- Act in the particular radio environment

The OODA loop is expected to work in complex radio environments, which are not totally random, but complex and reasonably stationary within some specific limits. This opens up for the development and use of intelligent systems capable to adapt to various networking conditions, also taking into account the end-to-end goals. Examples of cognition techniques are dynamic programming, learning machines, game theory, SDR and cross-layer protocol design [3]. The end-to-end goals refer to the network elements involved in the transfer of a data flow, e.g., routers, switches, interfaces, waveforms.

The second basic concept used in CRN is the cross-layer design [4]. This is basically a technique used to allow the exchange of information across different layers in the TCP/IP protocol stack. The goal is to improve the performance. This concept is advantageous for CRNs, where there are many parameters at low layers that are used in diverse optimization algorithms. On the other hand, the network flexibility and upgradeability may become limited.

III. Fundamental Operations

The fundamental point for CRD and CRN is that a CR enables the use, by Secondary User (SU), of temporally unused spectrum, the so-called Spectrum Opportunity (SOP) or White Space (WS), in the case the Primary User (PU) does not use it. On the other hand, in the case PU reuses the particular SOP, then SU must move to another SOP to keep the ongoing communication.

Formally, CRDs are expected to be able to work in complex radio environments, which can be best characterized with "multi" facilities:

- Multi-band
- Multi-channel
- Multi-mode
- Multi-standard
- Multi-service

The consequence is in form of high complexity of CRDs and CRNs, as they are requested to provide functionality for these situations. The four fundamental operations needed for management in this case are [5], [6]:

- Spectrum sensing, which is about the ability of a CR element to measure, sense, learn and be aware of a set of parameters regarding the wireless environment like, e.g., spectrum and power availability, characteristics of radio channel, network infrastructure. Some of the most popular methods for spectrum sensing are energy detection, waveform-based, cyclostationary-based, cooperative sensing, interference-based, prediction-based [5]. These methods have different advantages, drawbacks and performance.
- Spectrum management, which is about selecting the best spectrum opportunities (SOPs), out of the available ones, to form the best possible e2e route for a SU communication with reference to a given Qos/QoE. For doing this, one needs to first model and characterize the SOPs. This also demands for a good knowledge of the behavior of PUs. Finally, appropriate mechanisms for decision making are needed.
- Spectrum sharing, which refers to solving diverse conflicts that may happen in CRNs, e.g., when more SUs are forced to share the available spectrum at a particular time moment. The access of SUs must in this case be coordinated based on some adopted rule. This is primarily a Medium Access Control (MAC) question. Generally, there are two categories of spectrum access control mechanisms, namely, spectrum access and resource allocation. Control mechanisms of different types can be used for solving these problems, e.g., cooperative or non-cooperative mechanisms, overlay or underlay access, hybrid mechanisms.

- Spectrum mobility, which is about changing the communication channel as a consequence of changing operational conditions. This may for instance involve situations when a SU is forced to change the frequency band due to the appearance of a PU demanding for the particular communication channel. Spectrum mobility demands for very sophisticated control mechanisms, which are acting at different layers of the TCP/IP protocol stack. The goal is to provide the expected QoS/QoE irrespective of the changing operational conditions.

All together, these four fundamental operations provide communication in CRNs.

Practically, a CRD is expected to be able to:

- Identify the available SOPs, based on some particular criteria
- Dynamically select the route to a particular destination CRD
- Accordingly, to adapt different parameters like power, frequency/channel, code
- Adapt the route based on the particular network conditions, i.e., the so-called multi-dimensional routing and optimization
- Not disturb the ongoing PU communications
- Provide security measures

In other words, the CRD is expected to dynamically use for communication all types of available resources under the condition of avoiding the interference with PUs and other communicating SUs.

Furthermore, another important factor that influences these operations is regarding the interests of user and network operator. The user is particularly interested in telecommunication services offering higher bandwidth, more flexibility in selecting service providers and also access technology, reliability, security, Quality of Service (QoS)/Quality of Experience (QoE), low cost. On the other hand, the teleoperator is interested in lower complexity management, scalability, security, fault tolerance, good business models. The consequence is that these operations may become quite sophisticated.

IV. Heterogeneous Networks

An important aspect that heavily influences the future wireless networks is the appearance and popularity of heterogeneous wireless networks. Today, we can state that we are witnessing an evolution from macrocells to small cells of different dimensions, i.e., microcells, picocells and femtocells [7]. By this, a much denser architecture, based on cells of different dimensions and with different energy efficiencies, can be deployed. This is advantageous as it enables high data rates communication to multiple users, which is a direct effect of increasing energy efficiency resulting from the decrease in propagation distance. A positive effect is the reduction of transmission power needed for wireless communication as well as a potential more complex modulation scheme allowing for higher data rates. The drawback is in form of increased number of handovers as well as higher level of interference and complexity. Another important aspect is regarding the difficulties in deploying base stations in urban areas due to objections from homeowners and citizens.

Solving these problems demands for new technical solutions in form of cooperative algorithms and new network policies. The main technical challenges are interference mitigation, radio resource allocation, handover (both horizontal and vertical), self-organization. Other important challenges are solving the problems of delay spread and channel variation for high mobility users and cell edge located users. This is because geographical characteristics, operating frequency and vehicle velocity influence the radio characteristics. The existent solutions based on using Orthogonal Frequency Division Multiple Access (OFDMA) are limited in performance particularly because of the low tolerance to amplifier non-linearity and the requirement that each OFDMA subcarrier is orthogonal in order to maintain high spectral efficiency.

V. Cognitive Radio Networks

Today, there are several existing definitions of Cognitive Radio and Cognitive Radio Networks. The most important ones are the definitions provided by Federal Communications Commission (FCC) in the USA (2005), National Telecommunications and Information Administration (NTIA, 2005), International Telecommunications Union (2005), IEEE 1900.1 WG. Perhaps the best definition is the one provided by S. Haykin [8]:

"Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit power, carrier frequency and modulation strategy) in real-time, with two primary objectives in mind: highly reliable communications whenever and wherever needed; and efficient utilization of the radio spectrum".

Based on the above-mentioned spectrum management operations, a so-called Cognitive Framework (CF) has been defined for the control of communication in a cognitive radio network [2]. This is basically a software framework, which is used to map the high-level communication requirements to the underlying network, based on the particular cognitive process used for this. CF has three layers, which are dedicated to different functions. These are:

- End-to-end Goals (E2eG), which takes care of mapping the e2e goals (according to user requirements) into different policies and requirements for the cognition layer (part of Cognition Process).
- Cognition Process (CP), which consists of three layers, with distinct functions. These are specification language (to map the high-level user requirements into adequate language for the cognition layer), cognition layer (takes care of the cognition mechanisms) and network status

sensors (to provide feedback from the network to the cognition layer).

- Software Adapatable Network (SAN), which is composed by two elements, i.e., Network Application Programming Interface (API), to provide adequate interface to cognition layer, and configurable network status sensors, to provide feedback from the network to the cognition layer.

CF can be implemented in different ways, e.g., centralized, distributed, mixed.

A number of difficult questions must be answered in the development and building of CRNs. The most important ones are regarding the Dynamic Spectrum Access (DSA), the problem of network heterogeneity as well as the demand to provide communication with requested QoS/QoE.

Basically, a CRN/CRD continuously senses and collects different types of information regarding the wireless environment, e.g., traffic behaviour, interference conditions, local policy rules. This information can be categorized in three categories, namely, content, profiles and (local) policies (e.g., regarding spectrum access, security level). Based on the selected profile input as well as the set of policies existent in the particular context, CRN/CRD takes different decisions for the provision of communication services with requested QoS/QoE. This is also the result of adequate optimization algorithms used to provide the requested QoS/QoE level. Finally, these decisions are used as an input to some learning mechanisms used to improve the performance of decision making algorithm.

A list of popular cognition techniques that can be used in CF for the control of CRNs is as follows [2], [3]:

- Bayesian signal processing
- Dynamic programming
- Learning machines with feedback
- Game theory
- Dynamic frequency management
- Software defined radio
- Cross-layer protocol design

The other important element in CRNs is the cross-layer design. There are two cross-layer design approaches existing today [4]. These are the implicit cross-layer design and the explicit cross-layer design. Implicit design means that the reference layer architecture is not changed, whereas explicit design means that the layer architecture may change (e.g., merging or splitting of adjacent layers, improving the interaction between layers). The goal is to better allow for observing and altering low-layer parameters. Specific optimization algorithms can be used for this purpose, which are typically low-layer related, e.g., link-layer optimization, network-layer otimization, multi-network optimization.

At a network level, there are today two general categories of CRN architectures. These are based on the following concepts [9]:

- Vertical spectrum sharing, also known as TV White Spaces (TVWS). The basic concept is to use the VHF/UHF TV bands that become available after the analogue-to-digital TV switchover. This is a solution put forth by the USA and the UK. TVWS is under standardization by IEEE 802.22. The key challenges are not regarding spectrum sensing but to understand what is sensed. This is because the available spectrum is not the same in different locations. This means that location and time information must be first collected and processed in different locations to obtain space-time maps, the so-called geographic databases. Based on these maps, unlicensed users can use the available spectrum for communication provided of course that the licensed broadcast TV services are not affected. The interference mitigation is a sophisticated mechanism, which means that the TVWS devices become complex.
- Horizontal spectrum sharing, also known as infrastructure-based or infrastructure-less CRN. This is an architecture that is more popular in Europe, and it is under standardization by IEEE P.1900 WG. The main goal in this case is to expand the technological limits of 4G in terms of DSA, hardware and software such as to provide CR services as well. Besides solving technical questions, this also demands for developing of attractive business models for teleoperators given the status of CR users (they do not buy telco subscriptions). This further demands for answering different questions regarding the control over infrastructure resources, which belong to teleoperators.

Alltogether, one can state that CRN demands for solving different technical questions, in different domains and with different degrees of complexity. They have therefore been the focus for intensive standardization, research and development activities done in different forums, e.g., IEEE, ITU-T, ETSI, 3GPP, EU FP7, NSF, DARPA [3].

VI. Dynamic Spectrum Access

Today, one of the most active areas of research in cognitive radio is regarding the Dynamic Spectrum Access (DSA), which refers to the method used to detect and to access spectrum holes [10], [11]. This term is very broad and contains a number of elements like spectrum access, spectrum allocation, spectrum pooling, spectrum management, regulation activities [11]. The spectrum is allocated opportunistically and the goal is to achieve device-centric interference control and dynamic reuse of the spectrum.

There are three general categories of DSA, each of them with own advantages and drawbacks [10]:

- Between a licensed primary system and a license-free secondary system, e.g., used to access the digital TV spectrum.
- Within the same primary system (to share the 3G/4G spectrum), with the help of, e.g., femtocells.
- Between two primary systems used at spectrum trading among cellular operators.

Today, the first form of DSA is considered to be the most disruptive one, given that secondary users act in this case as spectrum scavengers. The spectrum sensing is done over a range of frequency bands, and opportunistic spectrum access is done on both temporal and spatial basis. This means that, e.g., UMTS bands not used by primary users at a particular time moment in a particular geographical region can be used by secondary users.

Furthermore, three categories of DSA can be defined with reference to the sharing model:

- Dynamic exclusive use model, which maintains the basic structure of the existing policy for spectrum regulation. The spectrum is allocated to certain services for exclusive use, at particular times and in particular geographic regions. This approach cannot eliminate the white space in spectrum, which may result from the bursty nature of the wireless traffic.
- Open sharing model, used by competing peer users to share the available spectrum in a spectral region. Different spectrum sharing strategies can be used in this case, e.g., centralized, distributed. Each method has particular advantages and drawbacks. This model is popular in diverse wireless services operating in industrial, scientific and medical environments.
- Hierarchical access model, where a hierarchical access model is used, with primary and secondary users. The basic idea is to open the licensed spectrum to secondary users provided that the interference perceived by the primary (licensees) users is limited.

Today, the hierarchical access model seems to be the most promising model. In a longer perspective, it is expected that DSA will go beyond the opportunistic spectrum access model and new technologies and policies will be developed for cognitive radio networks, able to access a portfolio of different spectrum types [11]. Examples of such spectrum types include licensed spectrum, unlicensed spectrum, leased spectrum. These devices are expected to be able to dynamically change the operating spectrum within the particular spectrum portfolio, and to do this on a "just-in-time" basis. Furthermore, the resources of the spectrum pool may depend on context, location, technology. Parameters like price, QoS and energy saving may be used in selecting the particular spectrum.

Another important future research direction is regarding the development of national and international interactive spectrum use maps, to provide information about spectrum availability in different places of the world. These maps may further allow for the evaluation and tunning of other key technologies like wide-band antennas and spectrum sensors.

Other difficult research questions related to DSA that need to be answered are regarding the development of theoretical models for the characterization of PHY and MAC layers, spectrum sensing, provision of adequate protection for PUs, solving possible conflicts among SUs in accessing the spectrum, provision of performance for SUs, provision of security measures, resource management, development of models for spectrum policy and economics, development of attractive business models.

VII. Security Issues

Security in CRNs is a difficult problem to solve, which so far has not been given much attention. The wireless networks are today vulnerable to security attacks. This is because of the nature of CR communication, with functionalities covering almost the entire TCP/IP protocol stack and using unlicensed spectrum for communication. Another reason is because of the processing of large amounts of information of different categories.

The use of CRN communication may have serious consequences like unsettle spectrum licensors and regulators. The question is how to protect the licensed spectrum and users and also how to avoid unlicensed users from causing interference with existing licensed users or use of special reserved frequencies like, e.g., for emergency services.

Other possible security risks are involuntary downloading of malicious software, licensed user emulation and selfish misbehaviour. In the most extreme cases attackers may disrupt the basic functions of an operating wireless network. Furthermore, another serious challenge is regarding the performance deterioration expected to happen in relation to the enforcement of security measures in CRNs.

Apart from the aforementioned vulnerabilities, there are other threats that are specific to CRNs. These include Objective Function Attacks (OFA), cross-layer attacks from physical/link layer to transport layer and Primary User Emulation (PUE) attacks [12].

The general demand is that communication systems based on CRN must guarantee, as a minimum, the same level of security as conventional wireless systems and hence satisfy communication security requirements like access control, confidentially and privacy, availability, authentication and authorisation. This is a consequence of the conformance to existing standards and regulations already defined for the wireless communication systems.

VIII. Conclusions

The paper has provided a short overview of cognitive radio networks and some of the most important technical challenges. These networks are expected to be part of the future generation wireless networks. They offer huge promises for users in terms of ability to freely move among different networks, obtaining cheap services as well as new advanced services and business models. At the same time, this technology demands for solving very complex research questions regarding dynamic spectrum access, multi-dimensional routing and optimization, security. Alltogether, there is high expectation that new technical solutions will appear to allow the advance and acceptance of the new technology.

REFERENCES

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

[2] Thomas R.W., Friend D.H., DaSilva L.A. and MacKenzie A.B., *Cognitive Networks: Adaptation and Learning to Achieve End-to-End Performance Objectives*, IEEE Communications Magazine, December 2006

[3] Popescu Alexandru, *Cognitive Radio Networks: Elements and Architectures*, PhD thesis, Blekinge Institute of Technology, Karlskrona, Sweden, in preparation

[4] Fortuna C. and Mohorcic M., *Trends in the Development of Communication Networks: Cognitive Networks*, Computer Networks, 53, Elsevier, 2009

[5] Akyildiz I., Lee W-Y. and Chowdhury K.R., *CRAHNs: Cognitive Radio Ad Hoc Networks*, Ad Hoc Networks, Elsevier, doi: 10.1016/j.adhoc.2009.01.001, 2009

[6] Popescu Alexandru, Erman D., Fiedler M., Popescu Adrian and Kouvatsos D., *A Middleware Framework for Communication in Cognitive Radio Networks*, International Congress on Ultra Modern Telecommunications and Control Systems, Moscow, Russia, 2010

[7] Hasan Z., Boostanimehr H. and Bhargava V., *Green Cellular Networks: A Survey, Some Reasearch Issues and Challenges*, IEEE Communications Surveys and Tutorials, Vol. 13, No. 4, Fourth Quarter 2011

[8] Haykin S., *Cognitive Radio: Brain-Empowered Wireless Communications*, IEEE Journal on Selected Areas in Communications, Vol. 23, No. 2, February 2005

[9] Steenkiste P., Sicker D., Minden G. and Raychaudhuri D., editors, *Future Directions in Cognitive Radio Network Research*, NSF Workshop Report, http://www.cs.cmu.edu/~prs/NSF_CRN_Report_Final.pdf, 2009

[10] Zhao Q. and Sadler B. M., *A Survey of Dynamic Spectrum Access*, IEEE Signal Processing Magazine, Vol. 24, Issue 3, May 2007

[11] Khalid L. and Anpalagan A., *Emerging Cognitive Radio Technology: Principles, Challenges and Opportunities*, Computers and Electrical Engineering Journal, Elsevier, doi: 10.1016/j.compeleceng.2009.03.004, May 2009

[12] Baldini G., Sturman T., Biswas A.R., Leschhorn R., Godor G. and Street M., *Security Aspects in Software Defined Radio and Cognitive Radio Networks: A Survey and A Way Ahead*, IEEE Communications Surveys and Tutorials, Vol. 14, No. 2, Second Quarter 2012