An Architecture for Cognitive Radio Networks with Cognition, Self-organization and Reconfiguration Capabilities

Ding Xu*, Qixun Zhang, Yang Liu, Ying Xu and Ping Zhang
Key Laboratory of Universal Wireless Communications, Ministry of Education
Beijing University of Posts and Telecommunications, Beijing, P.R. China.
Email: *xuding.bupt@gmail.com

***Abstract*—Cognitive radio is considered to be a key technology for future heterogeneous networks. Cognitive radio network is an evolution of the cognitive radio by extending the radio link scope to network scope, and is defined as a network that can observe its environment, make decisions based on the observations, and then reconfigure according to the decisions, all while taking into account the end-to-end goals. This paper proposes a high level abstraction of the cognitive radio network architecture. The operation of the proposed architecture is guided by the end-to-end goals. The proposed architecture consists of four components: *end-to-end goals management*, *cognition management*, *self-organization management*, and *reconfiguration management*. The proposed architecture provides the functionality to manage these components, enable communication between them, and facilitate the interfaces between cognitive radio network and its surrounding environment. In order to demonstrate the functionality of the proposed architecture, we present a use case of ubiquitous wireless access services and show that the proposed architecture enables ubiquitous connectivity with harmonized networks and integrated services.**

I. INTRODUCTION

Nowadays, various wireless communication technologies are swarming into our life, such as global system for mobile communications (GSM), European universal mobile telecommunications system (UMTS), wide-band code-division multiple access (WCDMA), and CDMA2000. However, these wireless access network technologies are separated and incompatible, thus the rapidly expanding service requirements can not be well satisfied. Therefore, it is necessary to harmonize separate networks and integrate various services. To provide ubiquitous connectivity with harmonized networks and integrated services, the radio should support multiple frequency bands, and multiple access modes, which are based on the awareness of its operational environment.

One of the most promising solutions for the above problem is the cognitive radio (CR), which presents a new approach to deal with the issue. CR, which is coined by Mitola from software defined radio (SDR), is defined as a radio that can dynamically change its transmitter parameters according to interactions with its operational environment [1]. It differs from traditional radio in that the CR can reconfigure its operational parameters based on the observations from the environment. One of the most famous applications of CR is the dynamic spectrum access (DSA) [2], which is proposed to solve the problem of spectrum scarcity. DSA can improve the spectrum efficiency through reusing the spectrum bands that are underutilized by the licensed primary networks.

However, CR is generally targeting at radio and is a link level technology for physical layer radio transmission. Thus, the concept of CR network (CRN) is proposed as an evolution of the CR [3]. CRN is defined as a network with cognition capability that can observe its environment, with self-organization capability that can make decisions based on the observation, and then reconfigure according to the decisions, all while taking into account the end-to-end goals. Here, the end-to-end denotes all the elements in the network which involve in the transmission of a data communication flow [4]. The end-to-end goals are what gives a CRN its network-wide scope and differs from CR, which has only a local, radio scope. In addition, from the definition of CRN, three main characteristics of CRN can be defined: *cognition capability*, *self-organization capability* and *reconfiguration capability*. The cognition capability refers to the ability to sense, obtain information from the current operational environment [5], such as information about spectrum band, power, etc. The self-organization capability provides ability to derive optimized parametrization based on the gathered information and the end-to-end goals [6]. The reconfiguration capability means the ability to reconfigure the operational parameters according to the optimized decisions.

In this paper, we propose a high level abstraction of the CRN architecture, which supports the three main characteristics of the CRN. The operation of the proposed architecture is guided by the end-to-end goals. It consists of four components: end-to-end goals management, cognition management, self-organization management, and reconfiguration management. The proposed CRN architecture provides the functionality to manage these components, enable communication between them, and facilitate the interfaces between CRN and its surrounding environment. It is noted that this paper is focusing on the high level of the CRN architecture while the detailed implementation schemes, e.g., interfaces and protocols, etc.,

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are left for future work.

The rest of the paper is organized as follows. Section II presents some related work to this paper. Section III presents the proposed high level abstraction of the CRN architecture, stressing the functionality to be provided and the interfaces among different components. Section IV illustrates the functionality of the proposed architecture by a use case. In section V, we draw some conclusions.

II. Related Work

There are a number of research studies that focus on architectures for CRN . In [2], Haykin proposed a simple DSA architecture, which emphasizes the need for CRN to be aware of its radio environment and avoid interference. In [4], Thomas proposed a cognitive framework for CRN to achieve the end-to-end goals, where a cognitive process layer is introduced to perform the cognitive functionality of CRN. In [7], Denkovski presented a policy reasoning architecture for CRN where a variety of policy types for different purposes allows for high network flexibility and adaptability. Besides, international standardization of CRN is being performed currently, including IEEE and European Telecommunications Standards Institute (ETSI). Specifically, IEEE dynamic spectrum access networks (DySPAN) standards committee (DySPAN-SC) proposed a functional architecture for CRN supporting DSA [8]. ETSI also proposed a functional architecture for CRN mainly focusing on reconfiguration capability [9] which is based on cognitive pilot channel [10]. However, the architectures in the above work only focus on some specific applications of CRN, the proposed architecture in this paper provides a high level abstraction of CRN, where the end-to-end goals and three key capabilities of CRN: cognition capability, self-organization capability and reconfiguration capability are all taken into consideration.

III. Cognitive Radio Network Architecture

The CRN architecture should describe the detailed mechanisms on how the end-to-end goals are achieved and how self-organized decisions and reconfiguration are performed. Therefore, the CRN architecture should provide 1) the cognition capability: the ability to sense, obtain information from its operational environment. 2) the self-organization capability: the ability to make optimized decisions based on the gathered information. 3) the reconfiguration capability: the ability to reconfigure the operational parameters according to the optimized decisions. 4) the ability to achieve the end-to-end goals. Fig. 1 illustrates the relationship between the architecture, end-to-end goals, cognition capability, self-organization capability and reconfiguration capability.

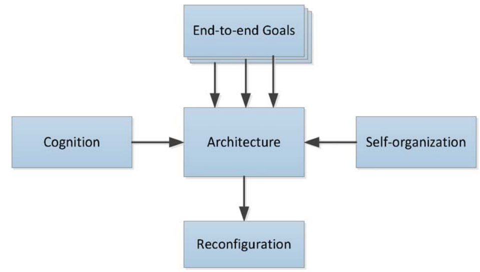

Figure 1. The relationship between the architecture, end-to-end goals, cognition capability, self-organization capability and reconfiguration capability.

Fig. 2 illustrates the proposed CRN architecture, which consists of four components: *end-to-end goals management*, *cognition management*, *self-organization management*, and *reconfiguration management*. The top-level component of the CRN architecture is the end-to-end goals management component, which drives the behavior of the entire CRN. Without the end-to-end goals management component guiding the operations of CRN, undesired situations may arise. The cognition management component is responsible for obtaining information from the environment and to deliver the information to other components in the architecture to better serve the current situation. The self-organization management component is responsible for deriving optimized decisions based on the gathered information and the end-to-end goals. The reconfiguration management component is responsible for reconfiguring the operational parameters according to the optimized decisions.

A. End-to-end Goals Management

As illustrated in Fig. 2, the end-to-end goals management component consists of two sub-components, namely end-to-end goals and cognitive specification language.

1) End-to-end goals: The end-to-end goals component is used to provide the operation goals of the entire CRN which drive the behavior of the CRN. The end-to-end-goals component's input may from users, network operators or applications. With end-to-end goals guiding the operations of the CRN, desired results can be achieved. Here, the scope of end-to-end includes all the network elements involved in a transmission data flow, such as gateways, switches, routers, protocols, modulation, coding, etc. At most of the time, there are multiple goals to be achieved, and it will not be possible to optimize all goals at the same time, thus a trade-off for each goal optimized on is needed. However, the Pareto optimal set [11], which is defined as the set of solutions by which no goal can be improved without deteriorating the others, can be achieved.

2) Cognitive specification language: The cognitive specification language component is responsible for translating the end-to-end goals to self-organization management component. We borrow the notion of cognitive specification language from [5] to provide behavioral guidance to the self-organization management component. Although end-to-end goals are network-wide, after the translation, the goals for the self-organization management component may be local to some network elements. Some candidates for cognitive specification language include radio knowledge representation language (RKRL) proposed by Mitola [12] for CR and numerous QoS specification languages [13] for multimedia services.

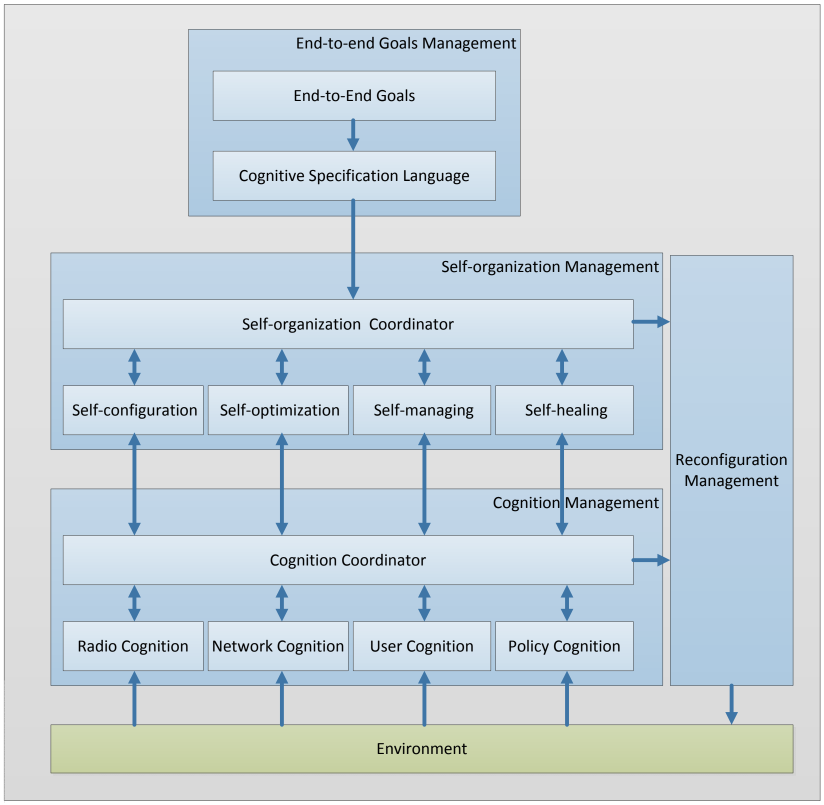

Figure 2. The cognitive radio network architecture.

B. Cognition Management

As can be seen in Fig. 2, the cognition management component consists of five sub-components, namely radio cognition, network cognition, user cognition, policy cognition and cognition coordinator. It is useful to partition cognition functionality according to their emphases and related cognitive operations. By partitioning the cognition functionality, cognitive functionality can be modularized and extensible.

1) Radio cognition: The radio cognition component is responsible for gathering two types of information that the CRN needs to be aware of, i.e., the information of external radio environment and internal radio platform. The information of radio environment includes information regarding the spectrum usage, interference distribution, signal to interference plus noise ratio (SINR), etc. The information of radio platform contains information about physical resources and computational resources of radio platform, such as information about the radio platform is power limited or unlimited, how many computational resources have been used.

2) Network cognition: The network cognition component's primary task is to gather the information about itself. The network information includes network traffic, network element load, delay, routing, scheduling, security, topology, etc. Such information may be obtained by periodically updating network status in the field.

3) User cognition: The primary goal of user cognition component is to understand the needs of both the service provider and the end users, including operation preferences like radio access preferences, performance requirements like access availability, service type, quality of service, etc and user location. For example, the user location information may be obtained by employing localization systems like global positioning system (GPS).

4) Policy cognition: The policy cognition component is to gather information regarding the policies that govern the CRN's operation. It is employed to guarantee the security and legality of the CRN's operations. The information about policies includes the radio frequency plan, interference power limits, etc.

5) Cognition coordinator: The four above mentioned cognition components may work alone for information gathering. But most often, they need to work together. The cognition coordinator component is responsible for the coordination and management of the interactions of the four cognition components. The cognition coordinator is also used to send the information to the self-configuration management component and reconfiguration management component. The advantage of using cognition coordinator is that the architecture is modularized and extensible in the sense that the cognition components can be added, replaced or updated independently without impacting the other components and the integrity of the whole architecture.

C. Self-organization Management

As illustrated in Fig. 2, the self-organization management component consists of five sub-components, that is, self-configuration, self-optimization, self-managing, self-healing and self-organization coordinator. It is useful to partition self-organization functionality according to their emphases and related self-organization operations. Thus, self-organization functionality can be modularized and extensible.

1) Self-configuration: The self-configuration component is used to obtain the necessary basic configuration for network operations and then initially configure the newly deployed network nodes by automatically installation procedures. It should be noted that the network nodes are still in pre-operational state after the initial configuration, but the nodes have connectivity to the network and can thus obtain additional configuration parameters from the network to become operational. From a user's perspective, it is plug and play, that is, there is no specific installation required [14]. For example, in 3GPP Long-Term Evolution (LTE) network, the home eNodeB can automatically configure itself and connect to the network.

2) Self-optimization: The self-optimization component is responsible for making optimized decisions based on the gathered information to auto-tune the network to achieve the end-to-end goals when the network is in the operational state, such as power and channel allocation [15], [16]. Considering that the complete information about the environment is impossible to be obtained, machine learning [17] can be adopted to improve the end-to-end performance through experience obtained over a period of time using incomplete information gathered. There are many candidate machine learning algorithms, e.g. artificial neural networks [18], genetic algorithm [19], reinforcement learning [20], [21], etc, can be used depending on what the end-to-end goals are and how network is organized.

3) Self-managing: The self-managing component is used to perform the operation and maintenance (O&M) tasks of the network. It enables shifting O&M from human operators to the network itself. The goals provided by the end-to-end goal management component provide high level guidance to O&M. The self-managing component can automatically act based on the information gathered by the cognition management component. Machine learning can also be used to gain knowledge about the environment for improving the end-to-end performance.

4) Self-healing: The self-healing component is responsible for detecting network problems and then solving or mitigating these problems to avoid deteriorating user experiences and reduce network maintenance costs. If a fault happens to a network node, the cognition management component shall detect the fault and transfer the necessary information to the self-healing component. When the self-healing component finds the fault, it uses the correlated information, does analysis, and then makes appropriate recovery decisions to solve the fault.

5) Self-organization coordinator: The four above mentioned self-organization components may work alone for decision making. But in most cases, they need to work together. The self-organization coordinator is used to coordinate and manage the interactions of the four self-organization components. The self-organization coordinator is also responsible for sending the decisions to the reconfiguration management component and receiving optimization goals from the end-to-end goals management component. Similar to the cognition coordinator, the advantage of using self-organization coordinator is that the architecture is modular and extensible in the sense that the self-organization components can be added, replaced or updated independently without impacting the other components and the integrity of the whole architecture.

D. Reconfiguration Management

As illustrated in Fig. 2, the reconfiguration management component is responsible for reconfiguring the network according to the decisions made by the self-organization management component and the information collected by the cognition management component. In the context of CRN, dynamic reconfiguration of the network include radio spectrum, transmit power, modulation and coding, radio access technologies, protocol stacks, network topology, routing, just to mention a few.

IV. USE CASE

In order to demonstrate the functionality of the proposed CRN architecture, this section illustrates a use case based on the architecture.

Fig. 3 demonstrates how the CRN architecture manages to provide the user with ubiquitous wireless access services. At first, the user is using his laptop computer and having a video conference with his colleague in his office. The laptop computer is connecting to the Internet through wireless local area network (WLAN). At 5 PM, it is time to go off work and go home to take care of children, but some business is still waiting to be discussed through the video conference. Thus the user determines to use his mobile phone to continue his video conference. The user cognition component discovers that the user is going to use his mobile phone instead of laptop computer. The radio cognition component checks the radio status of the mobile phone and finds that the mobile phone can connect to the WLAN to continue the session, and the self-optimization component (through self-organization coordinator) then sends a handoff query to the mobile phone. After necessary handoff procedures, the video conference session switches from the laptop computer to the mobile phone. When the user is on his way to taking a taxi, the radio cognition and network cognition components find that the user is moving outside the coverage of the WLAN, then the self-optimization component decides to switch the session to other wireless access networks. The network cognition component finds that WCDMA is available and the radio cognition component

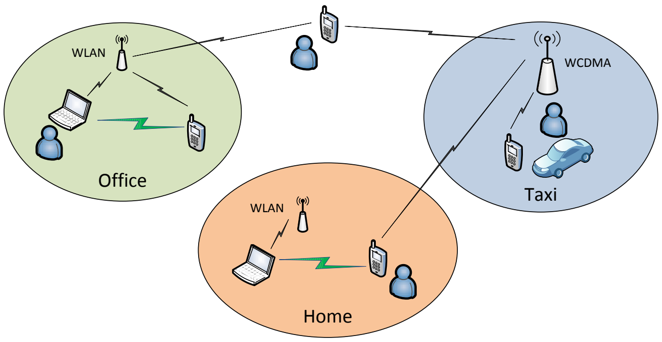

Figure 3. A use case of ubiquitous wireless access services in CRN.

finds that the mobile phone supports WCDMA, thus the self-optimization component sends a handoff query to the mobile phone to reconfigure itself to connect to WCDMA. Before the user moves outside the coverage of the WLAN, the session has been switched to WCDMA. When the user arrives home, the radio cognition component discovers that the mobile phone is running out of the battery power, thus the session must be quickly switched to another device. The radio cognition component finds that there is a laptop computer at home. The network cognition component discovers that WLAN is available at home and the radio cognition component finds that the laptop computer supports to connect to the WLAN. Then the self-optimization component sends a handoff query to the mobile phone. Before the mobile phone runs out of the battery power, the video conference session has been switched from the mobile phone to the laptop computer.

From the above use case, we see that by using the proposed CRN architecture, ubiquitous connectivity with harmonized networks and integrated services can be achieved.

V. Conclusions

This paper proposes a high level abstraction of the cognitive radio network architecture. The end-to-end goals guide the operations of the proposed architecture. The proposed architecture consists of four components: end-to-end goals management, cognition management, self-organization management, and reconfiguration management. The architecture provides the functionality to manage these components, enable communication between them, and facilitate the interfaces between cognitive radio network and its surrounding environment. The architecture is flexible and extensible in the sense that the components in the architecture can be added, replaced or updated independently without impacting the other components and the integrity of the whole architecture. In order to demonstrate the functionality of the proposed architecture, we present a use case of ubiquitous wireless access services and show that the proposed architecture enables ubiquitous connectivity with harmonized networks and integrated services.

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References

[1] I. Mitola, J. and J. Maguire, G.Q., "Cognitive radio: making software radios more personal," *IEEE Personal Communications*, vol. 6, no. 4, pp. 13 –18, Aug. 1999.

[2] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 2, pp. 201 – 220, Feb. 2005.

[3] N. Devroye, M. Vu, and V. Tarokh, "Cognitive radio networks," *IEEE Signal Processing Magazine*, vol. 25, no. 6, pp. 12–23, 2008.

[4] R. Thomas, D. Friend, L. DaSilva, and A. MacKenzie, "Cognitive networks: adaptation and learning to achieve end-to-end performance objectives," *IEEE Commun. Mag.*, vol. 44, no. 12, pp. 51–57, 2006.

[5] R. Thomas, L. DaSilva, and A. MacKenzie, "Cognitive networks," in *New Frontiers in Dynamic Spectrum Access Networks, IEEE International Symposium on*, 2005, pp. 352–360.

[6] FP7 End-to-End Efficiency (E3) Project. [Online]. Available: https://ict-e3.eu/

[7] D. Denkovski, V. Pavlovska, V. Atanasovski, and L. Gavrilovska, "Novel policy reasoning architecture for cognitive radio environments," in *Proc. IEEE GLOBECOM*, Dec. 2010.

[8] S. Buljore, H. Harada, S. Filin, P. Houze, K. Tsagkaris, O. Holland, K. Nolte, T. Farnham, and V. Ivanov, "Architecture and enablers for optimized radio resource usage in heterogeneous wireless access networks: the ieee 1900.4 working group," *IEEE Commun. Mag.*, vol. 47, no. 1, pp. 122–129, 2009.

[9] M. Mueck, A. Piipponen, K. Kalliojafirvi, G. Dimitrakopoulos, K. Tsagkaris, P. Demestichas, F. Casadevall, J. Perez-Romero, O. Sallent, G. Baldini *et al.*, "Etsi reconfigurable radio systems: status and future directions on software defined radio and cognitive radio standards," *IEEE Commun. Mag.*, vol. 48, no. 9, pp. 78–86, 2010.

[10] Z. Feng, Q. Zhang, F. Tian, L. Tan, and P. Zhang, "Novel research on cognitive pilot channel in cognitive wireless network," *Wireless Personal Communications*, vol. 62, no. 2, pp. 455–478, 2012.

[11] M. Osborne, "An introduction to game theory," 2003.

[12] J. Mitola, "Cognitive radio: An integrated agent architecture for software defined radio," Ph.D. dissertation, KTH, Stockholm, Sweden, Dec. 2000.

[13] J. Jin and K. Nahrstedt, "Qos specification languages for distributed multimedia applications: A survey and taxonomy," *Multimedia, IEEE*, vol. 11, no. 3, pp. 74–87, 2004.

[14] Z. Feng, Q. Zhang, D. Fan, L. Liang, and P. Zhang, "Self-configuration for wireless local area networks," *Journal of Network and Systems Management*, vol. 18, no. 1, pp. 43–63, 2010.

[15] D. Xu, Z. Feng, Y. Li, and P. Zhang, "Optimal power control of cognitive radio under SINR constraint with primary user's cooperation," *IEICE Trans. Commun.*, vol. 94, no. 09, pp. 2685–2689, 2011.

[16] D. Xu, Z. Feng, Y. Liu, and P. Zhang, "Outage probability minimising joint channel and power allocation for cognitive radio networks," *Electronics letters*, vol. 47, no. 25, pp. 1402–1404, 2011.

[17] M. Thathachar and P. Sastry, *Networks of learning automata: Techniques for online stochastic optimization*. Kluwer Academic Publishers, 2004.

[18] C. Peterson and B. Soderberg, *Artificial neural networks*. Blackwell Scientific Publications, Oxford, 1993.

[19] D. Whitley, "A genetic algorithm tutorial," *Statistics and computing*, vol. 4, no. 2, pp. 65–85, 1994.

[20] R. Sutton and A. Barto, *Reinforcement learning: An introduction*. Cambridge Univ Press, 1998, vol. 116.

[21] Z. Feng, L. Liang, L. Tan, and P. Zhang, "Q-learning based heterogenous network self-optimization for reconfigurable network with CPC assistance," *Science in China Series F: Information Sciences*, vol. 52, no. 12, pp. 2360–2368, 2009.