# FUNCTIONAL ARCHITECTURE FOR EFFICIENT CONTROL OF COGNITIVE RADIO SYSTEMS

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## ABSTRACT

This paper presents results of the European project E3 (End-to-End Efficiency).

Cognitive Radio Systems that have certain freedom for autonomic spectrum and technology usage decisions get more and more important. Especially opportunistic spectrum access has been extensively discussed during the last years. One of the results is that even those radio systems that act at a very high degree of autonomy need still some control. This results from the fact that a reliable resolution of coexistence issues with primary systems as well as between cognitive systems is required.

This paper considers the functional architecture that provides a frame for implementation of the remaining control in Cognitive Radio Systems.


## 1. INTRODUCTION

First, the paper discusses necessary control features supporting communication in a Cognitive Radio System. Different deployments of these systems are considered.

Than two complementing each other approaches of controlling Cognitive Radio Systems are considered in the paper:

a) Generally spoken, even if Cognitive radio systems to a large extend work without intervention from an external ("centralized") entity – there should be a way to set constraints for the access to radio resources by such a system. This "weak" external control – Cognitive System Governance (CSG) - is the first approach described.

b) Further, Cognitive Radio Systems will work only very seldom isolated from other radio systems. If those other systems change rapidly their use of radio resources then a cognitive system that accesses the same frequency resources must permanently observe its environment. Additionally, it needs means to communicate the results of these observations (measurements) between its radio nodes. This must happen fast enough to ensure at the one hand the quality of communication as requested and to satisfy at the other hand the agreements met with the other systems (usually to avoid interference above a given level). In order to keep a moderate level of sensing and messaging activities an efficient control is required. This internal control – Cognitive Control Radio (CCR) – is the second approach.

An appropriate functional architecture description follows.

Finally, co-existence issues with existing radio access technologies under conditions of opportunistic spectrum access are considered in the paper.

## 2. CONTROL IN COGNITIVE RADIO SYSTEMS

### 2.1. Cognitive System Governance

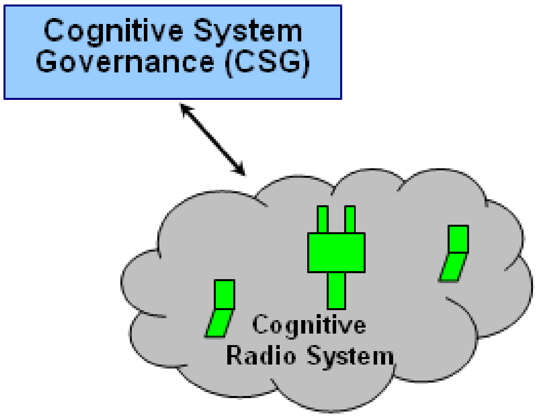


**Figure 1:** Governance of a Cognitive Radio System

Tasks of the Cognitive System Governance are:

1. Provide reliable information about WHERE and WHEN different spectrum bands MUST NOT be used for communication by the Cognitive Radio System. Especially, regulatory rules are included here.

   Spectrum broking and auctioning mechanisms

as well as different trading / spectrum exchange approaches ranging from long term leasing to on the fly spectrum exchanges can influence dynamically these data.
It is important to provide the information timely.

2. Merge spectrum usage constraint information from different authorities (e.g., from regulator and licensed operators) taking into account precedence rules. Depending on the deployment situation this can be done:
a) inside the CSG (the Cognitive Radio System interfaces to only one CSG entity),
b) inside the Cognitive Radio System (in this case multiple interfaces to different CSG entities are possible).
3. Help the Cognitive Radio System to detect secondary spectrum usage opportunities. The CSG may provide these opportunities in unordered, weighted, or prioritized manner.
4. Guide the Cognitive Radio System in its organization of sensing tasks. This will reduce time and power consuming for sensing.
CSG can provide, e.g., information about the characteristics of prioritized users that might appear spontaneously.
5. Be aware of the radio resource usage within the CSG area. Therefore, the CSG shall be updated with measurement and usage data collected from the Cognitive Radio Systems under its supervision. This update shall be organized and adapted accordingly to changing situations. Further, the CSG shall provide means for updating its data base from external sources (e.g., modifications of regulatory rules).

### 2.2. Cognitive Control Radio

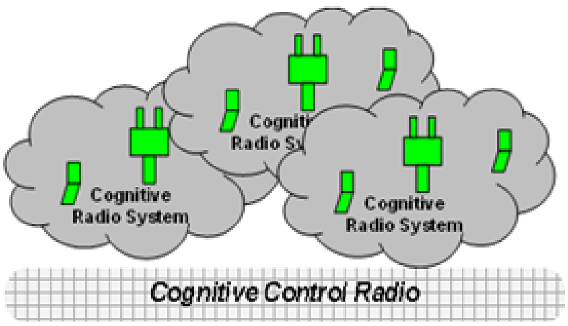


**Figure 2:** Cognitive Control Radio

The Cognitive Control Radio is the proposed way to handle co-existence as well as coordination issues between multiple Cognitive Radio Systems. Its tasks are:

1. Allow for negotiations about spectrum use between different systems/networks with dynamically changing system configurations.
2. Sharing spectrum sensing results and transmit/ receive parameters between systems/networks.
3. Require sensing activities in restricted geographical locations at a given time (overarching multiple systems/networks in that area are assumed)
4. Support a node after switch-on in finding a (cognitive) network to book in.
5. Further distribution of CSG rules. The CCR is an important means to inform all nodes of the covered Cognitive Radio Systems about the CSG rules. This is necessary because presumably (especially, in ad-hoc systems) not all nodes are able to receive CSG information directly.

It should be noted that the CCR does not care about

- Setup of radio communication between nodes of a Cognitive Radio Systems,
- Control of radio resource usage for an established radio link,
- Possible handover execution within one or between two Cognitive Radio System(s).

These are considered as functions that are inherent to the Radio Access Technology used in the Cognitive Radio System.

## 3. FUNCTIONAL ARCHITECTURE

The nodes of a Cognitive Radio System are considered to be belonging to one of two kinds: Normal node or master node.

Master nodes have two additional functions compared with the normal nodes:

a) Agent (or receiver) function for the CSG
b) Management within the CCR: Forwarding of CSG information (including information on necessary sensing actions), ordering sensing reports, broadcast of information on available Cognitive Radio Systems.

Via CCR, normal nodes have to inform their neighborhood on detected spectrum co-users. It is up to the masters to define what co-users are to be taken into account and what is the neighborhood (e.g., in terms of how many hops such information shall be forwarded). Normal nodes may ask for sensing actions in their neighborhood. Unexpected interference in ongoing communication shall also be reported by a normal node to its neighborhood.

It should further be noted that for CSG the master nodes communicate with CSG servers. At the other hand, CCR participants are only normal and master nodes.

### 3.1. Functional architecture of a normal node

Figure 3 shows the architecture of a normal node. Its radio system needs components to receive and transmit CCR messages. Further, the administration system shall include a CCR Server component.

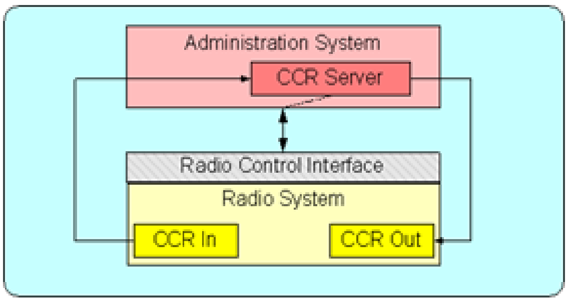


**Figure 3:** Functional architecture of normal node

The following functions are performed in the normal node:

1. All incoming CCR messages are forwarded to the CCR Server.
2. The CCR Server detects if the contained information is of relevance for the node or not. In case it is the appropriate action is taken (normally, internal data is updated accordingly).
   If, for example, the node functions as deciding node when establishing radio links – it needs to care on all the frequency usage policies/rules. Other nodes will follow them because of the access technology inherent signaling.
3. If the received message is a broadcast message and its forwarding counter is not equal to 0 this counter is decreased by one and the message is forwarded the CCR Out component for broadcast.
4. If the received message is a sensing trigger - the resulting sensing order is forwarded via the Radio Control Interface to the Radio System.
5. The Radio System forwards sensing results as requested to the CCR Server (most likely event driven, i.e. in case some relevant signal has been detected).
6. The CCR Server summarizes sensing results as requested and sends the resulting reports to the CCR Out component. The way this reports are sent depends on the triggering request: May be n-step broadcast to the neighborhood or a routed message to a master node.
7. The Radio System may ask the CCR Server for sensing actions in the neighborhood. The CCR Server in this case shall care about sending a broadcast message to the neighboring nodes with this request. Further incoming results shall be collected, summarized, and provided to the Radio System.
8. In case the Radio System detects a side-interferer in an ongoing radio communication it informs the CCR Server and via CCR Out a broadcast message is sent out.
   *Note:* The fact that in this case action has to be taken for the active radio link is not in the scope of this paper.

### 3.2. Functional architecture of a master node

Figure 4 shows the architecture of a master node. In addition to the components defined for a normal node its administration system contains an agent component for the CSG. It is responsible for handling request incoming from CSG server(s). The component that interfaces directly to the CSG server(s) is placed outside the administration system. Two options for the communication towards a CSG server are foreseen: a) via a wired link (preferred in case the master node has a wired connection to the internet), or b) via a radio link.

Another new component is foreseen in the administration system: A management server that realizes different common management functions appearing from the dynamic nature of the CSG.

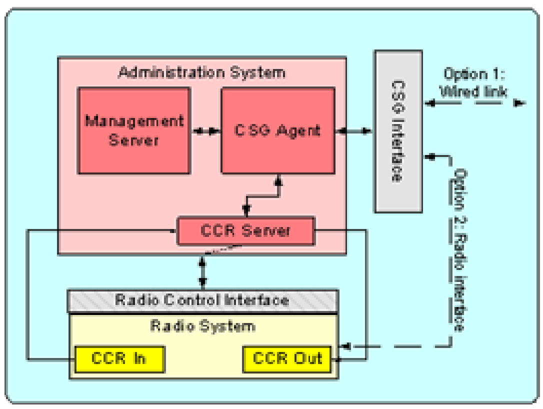


**Figure 4:** Functional architecture of master node

The following functions are performed in the master node in addition to those from the normal node:

1. Communicate with the CSG server(s): Book in/out, listen (or ask actively for changes if the server is a passive system).
2. Select and forward CSG information to other nodes in the neighborhood via CCR. Especially, spectrum usage rules that shall be known within the whole Cognitive Radio System have to be selected.
3. Store and follow the CSG rules on when and how to send reports (e.g., periodic measurement summaries, configuration changes, policy violations, unexpected interferer detections etc.) to the subscribed CSG server. This functionality is handled by the Management Server component.
4. The CSG Agent must generate sensing schemas in order to satisfy the reporting needs towards CSG. From these schemes the resulting sensing triggers are forwarded to the CCR Server.
5. The CSG Agent must generate notifications in case of the occurrence of certain events (changes in the configuration, failures, policy violations etc.) and forward them to the Management Server. Here – depending on the active ‘report subscriptions’ – the resulting reports are created and send to the CSG server(s).

### 3.3. CSG server functional architecture

In order to provide sufficient flexibility in the design of the CSG server side a cascaded approach shall be taken into account as an option. This leads to three different deployments:

a) The master node communicates directly with one CSG server only but indirectly with some more (that are higher in the CSG server hierarchy), see fig. 5.
b) The master node communicates with one CSG server only (directly as well as indirectly), see fig. 6.
c) The master node communicates directly with multiple CSG servers (a policy must be implemented inside the master node in order to establish the precedence between the servers), see fig. 7.

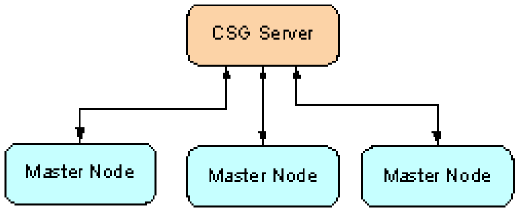


**Figure 5:** Master node and CSG server hierarchy

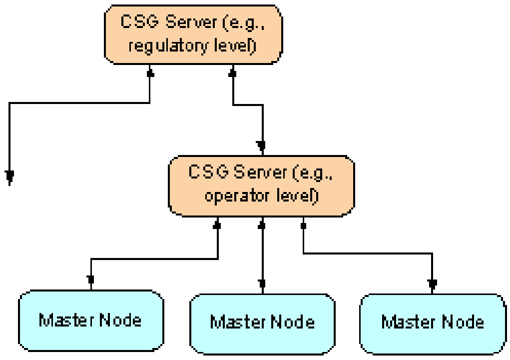


**Figure 6:** Master node has one CSG server

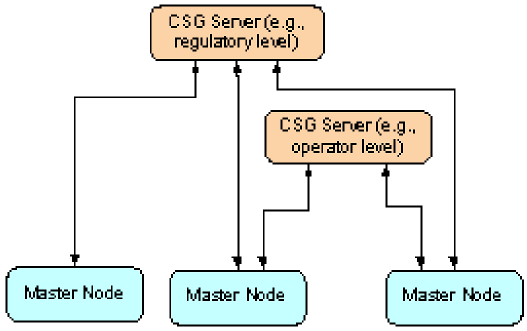


**Figure 7:** Master node has multiple CSG servers

Another problem for the CSG server is the kind of communication it has towards the master nodes. A very popular way is that the CSG server is just a maintained data base that has to be consulted by the master nodes (see fig. 8). The drawback of this solution is that the master nodes must have access to the data base via an internet access (i.e., simple ad-hoc networks from only wireless nodes are unable to do this).

A second way discussed very actively is the use of a so called Cognitive Pilot Channel (CPC, see fig. 9) implemented in a wireless technology. Here two sub-cases are important: a) broadcast only CPC, and b) CPC allowing up-link and down-link communication.

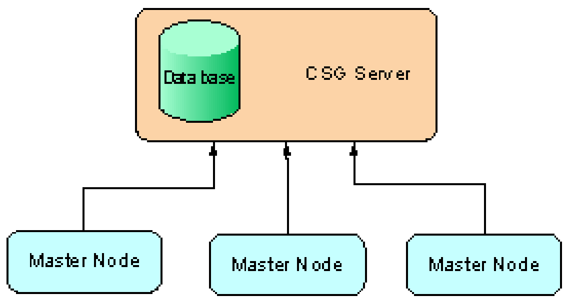


**Figure 8:** Data base centric CSG server

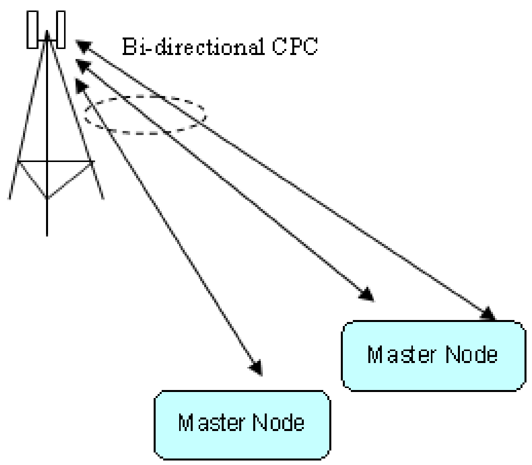


**Figure 9:** CPC approach

It should be noted that the use of CPC can save some CCR communication (forwarding of CSG information) because of the possibility of all nodes to receive CPC messages.

The following figure shows the basic functional architecture of a CSG server. It is laid out in a way that it fits into all the different approaches (with or without hierarchy).

The following functions are performed in the CSG server:

1. Receiving rules and/or policies from higher layer CSG server.
2. Sending context information towards higher layer CSG server.
3. Merging rules from higher layer CSG server with own rules.
4. Deriving policies from received context information and taking into account policies derived from higher layer CSG server.

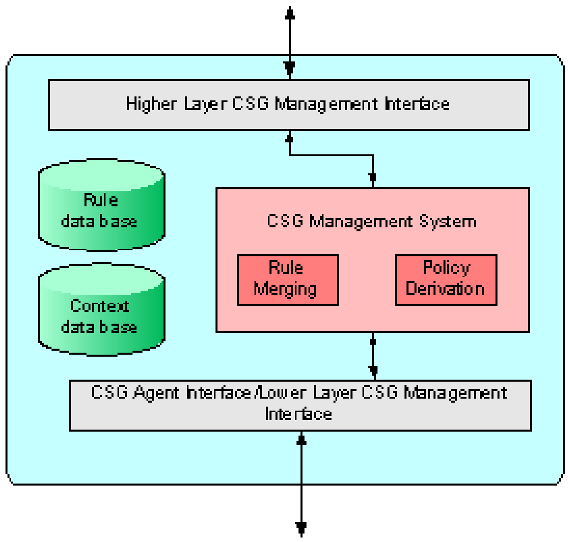


**Figure 10:** Functional architecture of the CSG server

5. Receive context information from master nodes (or lower layer CSG server).
6. Maintain a context data base.
7. Send rules and policies to master nodes or to lower layer CSG server.

## 4. CONCLUSION

The paper describes a functional architecture for the wide range of control tasks required for Cognitive Radio Systems.

Aspects of external governance as well as internal control are covered.

The external governance of a Cognitive Radio System involves:

- Dynamic control of measurements and reporting,
- Dynamic control of data summarization of measurement and context data at their origin,
- Policy driven management (policies are formally described as potential actions on objects representing the resources of the Cognitive Radio System)
- Data models for resources and management actions

The internal control of a Cognitive Radio System (except aspects inherent to a radio access technology) comprises:

- Spectrum usage negotiations between cognitive radio networks,
- Spectrum sensing collaboration between cognitive radio networks,
- Spectrum sensing results forwarding,
- Detection of suitable networks for a new node

The proposed architecture allows deploying of Cognitive Radio Systems with opportunistic spectrum access in e.g., in TV white space, in licensed spectrum of an operator's PLMN, in an unlicensed band or in any combination of them.

## 5. REFERENCES


[1] FCC Spectrum Policy Task Force, "Report of the Spectrum Efficiency Working Group," Nov. 2002, http://www.fcc.gov/sptf/files/SEWGFinalReport_1.pdf.

[2] J. Mitola III, "Cognitive radio: an integrated agent architecture for software defined radio," Ph.D. Thesis, KTH Royal Inst. Technology, Stockholm, Sweden, 2000.

[3] http://www.darpa.mil/sto/smallunitops/xg.html

[4] M. Krondorf et al "ORACLE - Opportunistic Radio Communications in Unlicensed Environments," ORACLE White Paper, Dec. 2006.

[5] G.Dimitrakopoulos, K.Moessner, C.Kloeck, D.Grandblaise, S.Gault, O.Sallent, K.Tsagkaris, P.Demestichas, "Adaptive Resource Management Platform for Future Cooperative Networks ", ACM/MONET (Mobile Networks and Applications), special issue on Reconfigurable Radio Technologies in Support of Ubiquitous Seamless Computing, Vol. 11, No 6, Dec. 2006, pages 799-811

[6] Z. Boufidis, E. Patouni, and N. Alonistioti, "End-to-End Reconfiguration Management and Control System Architecture," Project E2R II White Paper, Jun. 2007.

[7] M. Hasegawa, H. Harada, and S. Kato, "Research and development toward ubiquitous mobile communications," Microwave Photonics Workshop, Apr. 2007.

[8] H. Harada et al "A Software Defined Cognitive Radio System: Cognitive Wireless Clouds," IEEE Global Communications Conference (GLOBECOM 2007), Nov. 2007.

[9] IEEE P1900.4 PAR, "Architectural building blocks enabling networkdevice distributed decision making for optimized radio resource usage in heterogeneous wireless access networks," Oct. 2006.

[10] R.V. Prasad, P. Pawtczak, J.A. Hoffmeyer, and H.S. Berger, "Cognitive functionality in next generation wireless networks: standardization efforts," IEEE Communications Magazine, vol. 46, no. 4, pp. 72 – 78, Apr. 2008.

[11] G. Dimitrakopoulos et al "Functional architecture," Vehicular Technology Magazine, IEEE, Volume 4, Issue 1, March 2009 Page(s):42 - 48

[12] S. Buljore et al "Architecture and enablers for optimized radio resource usage in heterogeneous wireless access networks: The IEEE 1900.4 Working Group," Communications Magazine, IEEE Volume 47, Issue 1, January 2009 Page(s):122 – 129

[13] J. Pérez-Romero et al "Cognitive Pilot Channel: A Radio Enabler for Spectrum Awareness and Optimized Radio Resource Management," ICT-MobileSummit 2009, Conference Proceeding