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| **Radiocommunication Study Groups** |  |
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| Source: Document 5A/TEMP/348 | **Annex 9 to**  **Document 5A/788-E** |
| **19 November 2011** |
| **English only** |
| Annex 9 to Working Party 5A Chairman’s Report | |
| WORKING DOCUMENT TOWARDS A PRELIMINARY DRAFT NEW REPORT ITU-R [LMS.CRS2] | |
| [Cognitive radio systems [(CRS) applications] in the land mobile service] | |

*[Editor’s note: The title of the [LMS.CRS2] report will be considered in the 2012 meetings.]*

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# 1 Scope

*[Editor’s note: The text below will be revisited after the review of the contents of CRS2 report.]*

[This Report addresses the cognitive radio systems in the land mobile service (LMS) above 30 MHz (excluding IMT). The application of cognitive radio systems is presented and an analysis of the technical and operational characteristics of cognitive radio systems is given. The analysis includes the potential benefits and challenges of the technical and operational elements. It also present existing and emerging applications employing cognitive technologies and capabilities.

The report also introduces coexistence [aspect/scenarios] and the impact on the use of spectrum from a technical perspective.]

# 2 Introduction

*[Editor’s note: The text below will be revisited after the review of the contents of CRS2 report.]*

[Due to the rapidly increasing Internet/data traffic and the need of broader bandwidths, the studies in LMS have identified important aspects related to the use of CRS, cognitive technologies could be an enabler for different strategy of spectrum sharing on more dynamic basis, thus providing increased spectral efficiency of existing spectrum and mitigate the problem of congestion (e.g. capacity gain).

In the first CRS Report [LMS.CRS1], an introduction of CRS addressing technical features and capabilities, potential benefits and challenges has been [presented/given]. Also a description of deployment scenarios has been introduced.

Cognitive radio systems may provide several benefits to different [users] as described in ITU-R Report [LMS.CRS1], however the extent of the benefits and the suitability of the cognitive radio technologies depend on the deployments scenarios and use case of CRS as well as technical conditions of CRS operation.

In principle the introduction and deployment of cognitive radio systems can take place without the need for any changes in the Radio Regulation as CRS is not a radiocommunication service, [but a technology that] in the future may be implemented in wide range of applications in the land mobile service. However the deployment of CRS may require identification of unique and detailed characteristics to ensure operation in accordance with the provisions of the Radio Regulations, this can be achieved by future studies and further technical analysis.]

# 3 Related documents

## 3.1 ITU-R Recommendations

ITU-R M.1652 Dynamic frequency selection (DFS) in wireless access systems including radio local area networks for the purpose of protecting the radiodetermination service in the 5 GHz band.

ITU-R F.1110 Adaptive radio systems for frequencies below about 30 MHz.

ITU-R F.1337 Frequency management of adaptive HF radio systems and networks using FMCW oblique-incidence sounding.

ITU-R F.1611 Prediction methods for adaptive HF system planning and operation.

ITU-R M.1739 Protection criteria for wireless access systems, including radio local area networks, operating in the mobile service in accordance with Resolution 229 (WRC-03) in the bands 5 150-5 250 MHz, 5 250-5 350 MHz and 5 470‑5 725 MHz.

ITU-R F.1778 Channel access requirements for HF adaptive systems in the fixed service.

ITU-R SM.1266 Adaptive MF/HF systems.

## 3.2 ITU-R Reports

ITU-R M.2117 Software defined radio in the land mobile, amateur and amateur satellite services.

ITU-R M.2034 Impact of radar detection requirements of dynamic frequency selection on 5 GHz wireless access system receivers.

ITU-R M.[LMS.CRS1] Introduction to cognitive radio systems in the land mobile service.  
*[Editor’s note: Replace with final report number when assigned]*

ITU-R M.[IMT.CRS] Cognitive Radio Systems specific for IMT systems.  
*[Editor’s note: Replace with final report number when assigned]*

ITU-R SM.2152 Definitions of software-defined radio (SDR) and cognitive radio system (CRS).

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# 4 Definitions and terminology

The following definition and terms are used in the report.

## 4.1 Definitions

**Cognitive radio system (CRS)**: A radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained. (See Report ITU-R SM.2152)

Software-defined radio (SDR)

A radio transmitter and/or receiver employing a technology that allows the RF operating parameters including, but not limited to, frequency range, modulation type, or output power to be set or altered by software, excluding changes to operating parameters which occur during the normal pre-installed and predetermined operation of a radio according to a system specification or standard. (See Report ITU-R SM.2152)

## 4.2 Terminology

For the purpose of this report, the following terms have the meanings given below. However, these terms do not necessarily apply for other purposes.

Node

Node refers to a generic network element (e.g. a base station, an access points, radio terminals, core network element) that is involved in the related network operations. /

Programme Making and Special Events (PMSE)

Programme Making and Special Events (PMSE) is a term that denotes equipment that is used to support broadcasting, news gathering, theatrical productions and special events, such as culture events, concerts, sport events, conferences and trade fairs. PMSE devices use low power.

Policy

a) A set of rules governing the behavior of a system,

b) A machine interpretable instantiation of policy as defined in (a).

NOTE 1 – Policies may originate from regulators, manufacturers, network and system operators. A policy may define, for example, waveforms, radio resource control, and power levels.

System users may also be able to define preferences as long as they are consistent with the operator and regulatory policies.

NOTE 2 – Policies are normally applied post manufacturing of the radio as a configuration to a specific service application.

NOTE 3 – b) recognizes that in some contexts the term “policy” is assumed to refer to machine‑understandable policies.

TV White space

A portion of spectrum in a band allocated to the broadcasting service and used for television broadcasting that is identified by an administration as available for wireless communication at a given time in a given geographical area on a non-interfering and non-protected basis with regard to other services with a higher priority on a national basis.

## 4.3 Abbreviations

*[Editor’s note the following items will be revised accroding to the content of the Report.]*

AI Artificial Intelligence

A/D Analogue to Digital

ASM Advanced Spectrum Management

BCH Broadcast control Channel

BS Base Station

BTS Base Transceiver Station

BTSM BTS Management

CAPEX Capital Expenditure

CCC Cognitive Control Channel

CID Cognitive Information Database

CINR Carrier to Interference and Noise Ratio

COQ Channel Opportunity Quality

COQDO Channel Opportunity Quality Descending Order

CPC Cognition supporting Pilot Channel

CPICH Common Pilot Channel

COQ Channel Opportunity Quality

CRBS Cognitive Radio Base Station

CRT Cognitive Radio Terminal

CCs Cancellation Carriers

CDMA Code Division Multiple Access

CORBA Common Object Request Broker Architecture

CPU Central Processing Unit

CUAO Channel Utilization Ascending Order

DAA Detect And Avoid

D/A Digital to Analogue

DFS Dynamic Frequency Selection

DNP Dynamic Network Planning

DSA Dynamic Spectrum bandwidth Allocation

DVB-H Digital Video Broadcasting – Handheld

EIRP Equivalent Isotropically Radiated Power

E-UTRAN Evolved Universal Terrestrial Radio Access

FFT Fast Fourier Transform

FH Frequency Hopping

FPGA Field Programmable Gate Array

FSM Flexible Spectrum Management

FSU Flexible Spectrum Use

GPS Global Positioning System

GSM Global System for Mobile Communications

IEEE The Institute of Electrical and Electronics Engineers

IMT-2000 International Mobile Telecommunication – 2000

IMT-Advanced International Mobile Telecommunication – Advanced

IMT-2000 CDMA DS International Mobile Telecommunication – 2000 Code Division Multiple Access Direct Spread

JRRM Joint Radio Resource Management

JTRS Joint Tactical Radio System

LO Local Oscillator

LAN Local Area Network

LLC Logical Link Control

LMS Land Mobile Service

LTE Long Term Evolution

MAC Medium Access Control

NAT Network Address [Translator]

MWR Mobile Wireless Router

NRM Network Reconfiguration Manager

OFDM Orthogonal Frequency Division Multiplexing

OPEX Operating Expense/ Operating Expenditure/ Operational Expense/ Operational Expenditure

PHY [Physical] layer

PMSE Programme Making and Special Events

PROM Programmable Read Only Memory

QoS Quality of Service

RAT Radio Access Technology

RBS Reconfigurable Base Station

REM Radio Environment Map

RF Radio Frequency

RLAN Radio Local Area Network

RO Random Order

RRM Radio Resource Management

RSSI Received Signal Strength Indicator

SCA Software Communication Architecture

SDR Software Defined Radio

SINR Signal to Interference and Noise Ratio

SNR Signal to Noise Radio

SOA Service-Oriented Architecture

SW Subcarrier Weighting

TPC Transmit Power Control

UHF Ultra High Frequency

UMTS Universal Mobile Communications System

UWB Ultra Wide Band

VoIP Voice over IP

WRAN Wireless Regional Area Network

# 5 Applications

There are already existing or planned applications that employ some of the cognitive capabilities in order to obtain knowledge of their radio environment, with the aim to avoid creation of harmful interference. Based on the obtained knowledge they are able to select parameters such as their frequencies and/or adjust their transmit power.

*[Editor’s note: we need to expand the introductory text to applications. Further contribution is required for the next meeting.]*

These applications are in the area of opportunistic spectrum use.

There are also a number of potential applications, which may cover also other deployment scenarios.

## 5.1 Existing and emerging applications employing cognitive capabilities

*[Editor’s note: The words “application” and/or “device” should be reviewed with a view to replacing them with appropriate word.]*

There are already examples of existing or emerging applications employing cognitive capabilities, such as sensing and geo-location with access to database. These example applications can also make decisions and adjust their operational parameters based on the obtained knowledge.

Both examples that are introduced in this section represent opportunistic use of spectrum: an existing example is the RLAN using 5 GHz band and the emerging application is the TV White Space usage.

### 5.1.1 5 GHz RLANs utilizing dynamic frequency selection (DFS)

An existing example of opportunistic spectrum use is RLAN’s operating in the 5 GHz spectrum range, based on their sensing capability.

Radio Local Area Networks (RLANs) can operate in the 5 250-5 350 MHz and 5 470-5 725 MHz bands on a co-primary basis with radiolocation systems, radars. RLANs operate within the mobile service allocation and radars in the radiolocation service allocation, both having a co-primary status. In this band, radio regulations have been adopted by the ITU (cf. Resolution 229 (WRC-03)) to facilitate sharing between the two systems with the aid of a dynamic frequency selection (DFS) protocol (cf. Recommendation ITU-R M.1652). This protocol specifies the sensing/detection and operational techniques to be used by the RLANs to avoid interference to the radar systems. Recommendation ITU-R M.1739 provides the protection criteria. Prior to operation, RLANs are required to use DFS to ensure that radiolocation systems are not operating in the same channel they intend to use. The mobile systems must also vacate channels when new radiolocation systems come into operation.

### 5.1.2 Use of TV White Space

Due to various reasons some channels have had to be left unused by TV applications to provide guard bands between the active broadcast channels. The guard bands have been needed to accommodate TV receiver characteristics for strong or weak signals and adjacent channel performance. Some channels have also been left unused as there has been limited TV service deployment in some geographic areas.

Recently, some administrations have allowed or are considering to allow license-exempt devices to operate on a non-interfering basis within these TV white spaces. To facilitate spectrum sharing and to protect incumbent services from interference, a variety of technical approaches for the operation in these bands have been considered. These approaches include:

– geo-location capability with access to a database,

– sensing capability

– use of a beacon

With respect to the capabilities of CRS to obtain knowledge of its environment, in the case of TV WS the key capability is the geo-location coupled with the access to a database. One administration adopted rules in September 2010 [FCC10-174] to allow license-exempt devices employing geo‑location/database access capabilities to access available channels in the UHF television bands*.*

Other administrations are also considering the requirements for the operation of the devices using TV White Space. Their considerations may result in somewhat different requirements.

## 5.2 Potential applications

The following subsections address the potentialapplications of CRS. Each of them uses either one or combinations of the deployment scenarios identified in Report [LMS.CRS1].

### 5.2.1 Cognitive Networks exploiting reconfigurable nodes

Cognitive Networks are the application of CRS to the network domain. In particular, a Cognitive Network is a network that could dynamically adapt its parameters, functions and resources on the basis of the knowledge of its environment.

In the context of this section, Cognitive Networks are intended to be deployed using reconfigurable nodes. In principle, the application of such Cognitive Network includes the following functionalities and entities:

− cognitive network management;

− reconfigurable base stations;

− reconfigurable terminals.

The cognitive network management functionality spans over different RATs, managing and controlling the nodes inside the network, with the goal to self-adapt towards an optimal mix of supported RATs and frequency bands. This functionality could act on the basis of some input parameters, for example the available resources, the traffic demand, the capabilities of the mobiles within the network (supported RATs, frequency bands, etc.), the requested bearer services (bandwidth, QoS, etc.), etc. In addition, this functionality could exploit a collaborative cognitive radio resource management scheme, where the decision making functions are shared among different network nodes.

In this approach, the reconfigurable base stations are the nodes establishing the Cognitive Network. The hardware resources of a reconfigurable base station could be dynamically reconfigured in order to be used with different RATs, frequencies, channels, etc., and they could support multi-RAT operation with dynamic load-management.

The reconfigurable terminals are the nodes connecting to the base station in the Cognitive Network. The software and hardware of a terminal could be reconfigured dynamically. Thus it could support operating on different RATs, frequencies, resource utilization modes, etc. Therefore, the reconfigurable terminals could facilitate the flexible and efficient adaptation of the Cognitive Network to the dynamic environment. For example, they could support multi-RAT operation, such as joint admission control and vertical handoff to balance the load of different RATs more efficiently.

In addition, Cognitive Networks enable the introduction of the cognition radio concepts and technologies in a multi-RAT environment.

The availability of reconfigurable base stations in conjunction with cognitive network management functionalities could give the network operators the means for managing the radio and hardware resource pool with overall efficiency. This enables to adapt the network to the dynamic variations of the traffic within the network.

The Cognitive Networks are shown to be a relevant application of the CRS in the network domain. The main features of Cognitive Networks can be summarized as follows:

− the dynamic self adaptation of the network configuration towards an optimal mix of supported RATs and frequency bands can be achieved by the exploitation of the reconfigurable nodes and the application of cognitive network management functionalities;

− the dynamic self adaptation (e.g. network configuration) can be based on the traffic patterns variations in time and space for the different deployed RATs;

− Ability to provide the sufficient information to the terminals for initiating a communication session appropriately in a dynamic context (e.g. CPC)

The potential application of Cognitive Networks described in this section refers to the scenario outlined in section 6.1.1.

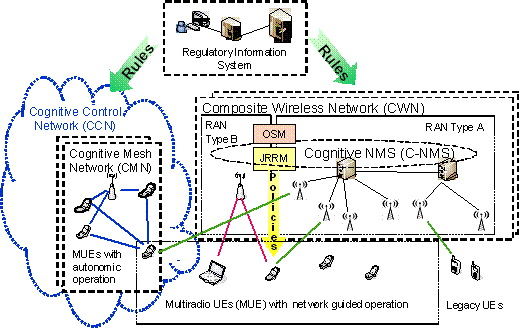
### 5.2.2 Cognitive mesh networks

In addition to the centralized concept described in the above section, decentralized CRS concept may also be considered as illustrated in the left part of Figure 3 [22[ET09a]].

FIGURE 3

Centralized and decentralized CRS concepts

*[Editor’s note: The description should be on a Cogntive Mesh Network and needs to be revised so that the terms are more general.]*



In Figure 3, Multi-radio User Equipment (MUE) represents a user device with reconfigurable radio capabilities and able to have connections to multiple radio networks at the same time. Such radio networks can be identified as i) Composite Wireless Network (CWN) representing a set of radio networks operated by a network operator using a common network management system that may also have cognitive capacity (see 6.2.1), and ii) Cognitive Mesh Networks (CMNs).In general, mesh networks can be seen as a group of nodes which all communicate with each other creating (typically using short-range radios) a mesh. Every node can send and receive messages, but the nodes may also function as routers. Cognitive Mesh Networks introduce the possibility to use opportunistic spectrum access in collaborative manner so that different CMNs active in the same geographical area can coordinate their use of radio frequencies. Interworking between CMNs may be arranged in a decentralized manner by using logically separate Cognitive Control Network (CCN) to share information between CMNs. CCN may be implemented with the Cognitive Control Channel (CCC) which is described in Section 6.4.1.1.1.

It should be noted that a MUE could be simultaneously connected to both CMN and CWN, however, the CMN domain is separated by the CWN domain, in terms of used radio frequencies and RATs. Inside CMN domain, MUEs do not act as relay entities towards CWN for others MUEs, while each of them may connect directly to CWN by the appropriate RAT [29[ET09a]].

### 5.2.3 Cross-device and cross-network handover

Cross-device and cross-network handover application is considered within heterogeneous radio environment, where one or several operators operate multiple radio access networks on different frequency bands assigned to them.

The terminals can make reconfiguration decisions autonomously or within framework provided by management from the network side. In both scenarios, the terminals have capabilities to obtain knowledge required for decision making, e.g. sensing capabilities and capability to access the ubiquitous networking server.

An example of cross-device and cross-network handover application is shown in Figure 4 [13[In05]]. In this example reconfigurable terminal performs cross-network handover and cross‑device handover. To support decision making to select parameters and attaching devices inside reconfigurable terminal, common signalling channel between ubiquitous networking server and the terminal is used to obtain knowledge in addition to the sensing. In the figure, the signalling is transferred by the same path with one of data paths the terminal using (as shown in orange solid lines for mobile terminals and the orange dotted lines for other devices). Another example is shown in Figure 5 [14 [Wu02]]. The figure shows the same potential application with different implementation of CRS features. The example implements a dedicated radio system as the common signalling channel shown in an orange arrow, named Basic Access Network (BAN) in [14 [Wu02]], between BAN-BS and BAN-component. Terminals exchange information with management entity on network, named Signaling Home Agent (SHA), for adjusting its parameter and selection of RANs.

FIGURE 4

Cross-device and cross-network handover

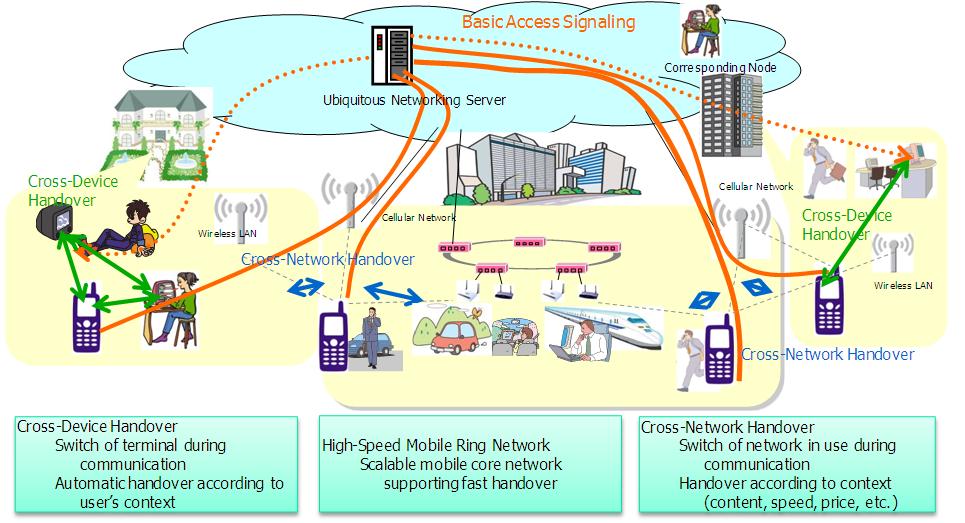


FIGURE 5

Dedicated radio system for common signaling channel

Fig5

### 5.2.4 CRS-assisted Inter-RAT handover

CRS-assisted Inter-RAT handover application is also considered within heterogeneous radio environment, where multiple radio access networks on different frequency bands coexist. Some terminals have reconfiguration capability. The terminals in this scenario have capability to support several simultaneous connections with different radio access networks.

An example of CRS-assisted inter-RAT handover is shown in Figure 6 [15[Ha07]] [16 [MH08]] [17 [Is08a]]. The green solid lines show the data paths and the orange dotted lines show the signalling. In this example reconfigurable terminal performs an inter-RAT handover. Also, reconfigurable terminal supports multiple simultaneous links with different radio access networks.

The terminal utilizes multiple wireless networks concurrently so that communication bandwidth for applications becomes large. Following terminal movement and/or change of radio environment, suitable wireless link(s) are adaptively and actively utilized in order to keep stability.

FIGURE 6

CRS-assisted inter-RAT handover

fig5.emf

### 5.2.5 Mobile wireless router

A mobile wireless router application is also considered within heterogeneous radio environment, where one or several operators operate multiple radio access networks on different frequency bands assigned to them.

Compared to previous two potential applications, this application can also address terminals without reconfiguration capability. A mobile wireless router serves as a bridge between multiple radio systems and terminals. Such mobile wireless router is required to have a CRS capability to obtain knowledge which RANs (RLANs and mobile networks) are available at its location, and also to adjust its operational parameters and/or switch the attaching radio access systems. The thresholds are configured by the obtained users’ preferences and they are used for RAN’s selection

One example of mobile wireless router application is shown in Figure 7 [18[Is08b]] [19[Ha08]] [20[Ha09]]. In this example mobile wireless router (MWR) reconfigures itself to provide the best suitable service for its terminals.

The MWR conducts Network Address Translation (NAT) routing between the Internet and local wireless network to which terminals are connected. When the MWR is turned on, the best frequency channel is selected, e.g. based on the lowest interference level. Then the MWR selects and conducts the various RAN authentication procedures according to the selected RAN.

FIGURE 7

Mobile wireless router

fig6.emf

### 5.2.6 Network configuration of three radio systems in service

Within a heterogeneous radio environment, a network configuration of three radio systems in service is considered. A system block diagram is shown in Figure 8, where one service provider deploys three radios systems on different frequency bands. These systems have different coverage areas from small to large cell. The resource manager collects the radio operation environment information from the base stations and user terminals on the geo-location basis, which is one of CR functionality (obtaining knowledge). The radio environment information may include the information of signal strength, throughput, and system delay. The resource manager provides the information to the control equipment. Based on this information, the control equipment selects the appropriate connectivity for the user terminal, which is another one of CR functionality (decision and adjustment)..

*[Editor’s note: “IMT-2000 WCDMA DS” and “ IMT-2000 OFDMA TDD MAN” should be generic words, e.g. WCDMA system, TDD system.]*

FIGURE 8

Network configuration consisting of three radio systems

Base Station





IMT-2000 OFDMA TDD WMAN

Internet



Application

Server

Resource Manager

(collection of radio circumstance information)

Heterogeneous radio network



IMT-2000 CDMA Direct Spread

RLAN

Controll Equipment

Base Station

User

terminal

#### 5.2.7 Opportunistic spectrum access in heterogeneous radio environment

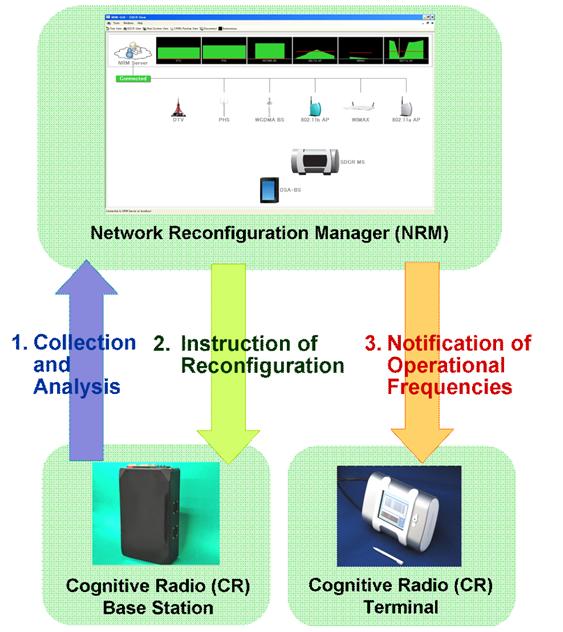
Opportunistic spectrum access is here considered within a heterogeneous radioenvironment, where particular frequency band(s) can be shared by several radio systems in order to optimize spectrum usage. Improvement in spectrum usage is based on the fact that different radio systems in the same geographic area at some time intervals may have different levels of spectrum usage.

One possibility in this scenario is that one radio system is not a CRS but another radio system is. Another possibility is that both radio systems are CRSs.

One example of opportunistic spectrum access is shown in Figure 9 [19[Ha08]], [20[Ha09]] based on the example 2 of use case of “Use of CRS technology as an enabler for opportunistic spectrum access in bands shared with other systems and services” described in Section 6.1.3 combined with “centralized decision making” described in Section 5.1.2.1.1. In this example base station and terminals with cognitive capabilities of obtain knowledge to sense the spectrum usage at their location. The sensing information of base station and terminals are gathered to Network Reconfiguration Manager (NRM) [IEEEP1900.4], which has a CRS capability of decision making. The NRM analyzes the measurements and detect temporary vacant frequency bands. Then, the NRM instructs the base station to reconfigure correspondingly. After the base station reconfigures itself to use these vacant frequency bands and starts its operation, NRM notifies the terminals of the operation frequencies of the base stations.

FIGURE 9

Opportunistic spectrum access in heterogeneous radio environment



### 5.2.8 Universal access

In a multi-RAT environment, universal access means providing users with the optimal wireless access that best suits the users’ needs as well as operators’ objectives towards efficient use of radio resource and spectrum.

In order to implement such universal access functionality, the technical characteristics and capabilities of CRS described in Section 5.1 should be exploited by the system. The universal access functionality consists of RAT discovery, RAT selection, and terminal reconfiguration. A terminal discovers RATs available and selects an optimal RAT among them by obtaining knowledge of its operational and geographical environment, established policies provided by the network and internal state. After an optimal RAT is selected, the terminal adjusts its parameters and protocols dynamically and autonomously according to its obtained knowledge and the network policies by reconfiguration procedure. There may be cooperation between terminals and wireless networks for the universal access functionality to find an optimal wireless access, for example, through Cognitive Pilot Channel.

Figure 10 shows the functional architecture of universal access.

The functional architecture of universal access is based on IEEE P1900.4 [IEEEP1900-4] and IEEE802.21 [IEEE802-21]. Entities from IEEE P1900.4 are applied for the optimization of radio resource management including dynamic spectrum use and an entity from IEEE802.21 is used as a toolbox for handover between heterogeneous radio access networks. A terminal may have various kinds of radio access technologies through SDR technology and it reconfigures its parameters in order to access an optimal RAT determined by the universal access functionality. Context information of the core network is transferred to terminals through either out-band CPC or in-band CPC, which are used for RAT discovery and selection procedures whenever terminals require context information of access networks.

Figure 10

Functional architecture for universal access



# **6** Cognitive Radio Systems **Operational techniques**



*Figure 11 [Editor’s note: Title of the figure will be provided at the next meeting.]*

*[Editor’s note: Figure 11 above need figure caption and brief explanatory text.]*

*[Editor’s note: The text below needs further revision.]*

The usage of the spectrum may vary over the time and over different locations and in such case CRS can improve the efficiency and flexibility of spectrum usage while operating in accordance with national and international radiocommunication regulations. There can be several technical approaches of CRS to improve the efficiency and flexibility to spectrum usage. The approaches can be distributed or centralized. Technical approaches include for example:

– obtaining knowledge of spectrum that is unoccupied on a temporal and geographic basis and use it in accordance with national and international regulation;

– coexistence with each other or other radiocommunication systems by detecting usage and reconfiguring itself to avoid harmful interference;

– using transmitter power control, a CRS could use the minimum power necessary to close the link at a given time, facilitating co-existence and using power efficiently;

– rerouting traffic through other paths when interference occurs;

– reconfiguring terminal connections between different radio systems, according to network situation (e.g. spectrum usage, traffic load, etc.);

– adapting dynamically and collaborating with each other and with other systems;

– redistributing the spectrum resources within different radio systems e.g. on the basis of traffic load and;

– aggregating several separate spectral segments in its working range to ensure bandwidth for communications.

It should be noted that some of the above examples could improve both the spectrum flexibility and spectrum efficiency, while in some examples these may be mutually exclusive.

It should also be noted that the implementation and deployment of CRS towards its full fledged concept may progress stepwise due to a number of technical challenges coupled with the current state of the technology.

### 6.1 Obtaining knowledge

*[Editor’s note: The introductory text should be more generic.]*

Three most commonly suggested methods for obtaining knowledge in CRS are listening to a wireless control channels, spectrum sensing and access to databases. They are covered in detail in the following sections. Also combinations of the methods can be considered.

#### 6.1.1 Listening to a wireless control channel

Control channels could be used for transmitting control information between two or more entities belonging to the systems which use the same spectrum resources. They facilitate more efficient CRS operation, spectrum use and coexistence of different radio systems. One of the key challenges with control channels is to decide how much and what control information should be shared to find the balance between the increased overhead and the gain achieved from sharing that information. There also needs to be a way to ensure the reliability and accuracy of the control information sent on the channel. Following we have two examples of such control channels. Cognitive Control Channel (CCC) which may enable different cognitive radio systems to exchange information related to the local spectrum between each other, and Cognitive Pilot Channel (CPC) via which the cognitive radio system obtains knowledge on radio operational environment and by doing this facilitates the efficient operation and spectrum use. It may be possible to use or extend control channels already defined for the existing radio systems operation for cognitive control information sharing.

The purpose of CCC is to enable distributed information sharing directly between the CRS entities which have operation in the same area, whereas CPC conveys elements of the necessary information to let the mobile terminal know e.g. operators, policies, and access technologies and their associated assigned frequencies in a given region to enable efficient RAT discovery and selection. CPC covers the geographical areas using a cellular approach. The focus of CCC is on enhancing coexistence between secondary systems which are using the same available spectrum resources, i.e. the networks operating in the same area and frequency band.

##### 6.1.1.1 Cognitive Control Channel

The Cognitive Control Channel (CCC) is a suggested approach for a real time communication channel between different distributed CRS components in a specific geographical area. The CCC is primarily targeted for enhancing the coordination of the CRS devices. The CCC enables different CRS entities to exchange information related to the coexistence, spectrum usage rules or policies and/or specific capabilities and needs of different entities. The CCC may be used for:

– Coexistence – Sharing the information on the network capabilities and characteristics, network’s spectrum need and use, and agreeing spectrum use with other networks in the area.

– Cooperative sensing – Agreeing on the common quiet periods for sensing the signal from other radio nodes which are not connected to the CCC, and sharing spectrum results between the other networks in the area.

– Network access – Discovering the networks or devices to connect to, their capabilities and provided services.

– Access local policy and etiquette information, e.g. sharing rules for accessing specific bands and local availability of the bands.

The CCC may operate on a physical or a logical channel. If operating on a physical channel, a radio targeted for cognitive control channel would need to be included in the entities sharing cognitive control information. This would enable direct communication between any entities within the range of the used control radio. Alternatively the CCC could operate as a logical channel on any physical links. If the entities do not support the same connectivity means, direct communication between the entities is not possible.

However, entities which have to share cognitive control information may connect over the internet or through wireless router nodes.

*[Editor’s note: The “scenario” in the text below should be checked throughout the document. The word “scenario” below is not identical to the scenarios in CRS1 report. The word needs to be changed.]*

The CCC can be applied e.g. in a scenario of heterogeneous networks, consisting of centralized and decentralized CR system concepts, operating in the same area. This type of [scenario] is shown in Figure 3 in Section 5.2.2.The CCC enables the networks to share and exchange various information directly with each other to enhance simultaneous operation.

The information which a network may share on the CCC can be collected by a combination of means, e.g.:

– Querying a local database for spectrum availability.

– Spectrum sensing, e.g. estimating spectrum availability or recognizing other spectrum users by evaluating the detected radio waves.

– Information received from other CRS entities e.g. over CCC or CPC.

###### 6.1.1.1.1 **CCC** operation procedure

[*Editor’s note: brief introduction which describes the concept of CCC (Reference XXXX). The text should be revised, considering the balance between CPC and CCC in terms of their text volume.*]

[Typical use scenarios of the CCC in an environment of independent and/or heterogeneous networks are illustrated in Figure 12. The networks which use locally the same spectrum resources share cognitive control information to each other over the illustrated CCC connections. If the physical implementation option of the CCC is used, direct CCC connections may be formed over low power local connectivity technology between the networks. In the logical channel implementation option of the CCC, a CCC entity in the backhaul would be needed to facilitate the connections between appropriate networks.

Figure 12

Cognitive Control Channel used for enhancing coexistence between heterogeneous networks



When a network starts operation, for example an access point or a base station is switched on, it does not know which other networks operate in the same area and may utilize the same spectrum. If the network determines that cognitive control information sharing with those other networks is required or useful, it initiates the CCC operation. The CCC operation procedure is organized in four phases:

• initiate CCC operation;

• discover other networks;

• connect to the relevant networks;

• share and receive information with the relevant networks.

The CRS behaviour in different states depends on whether the physical or logical implementation option is used for CCC.

In “Initiate CCC operation” phase the CCC entity in the CRS network activates the CCC operation. In the physical implementation option it switches on the local connectivity technology which is used for CCC. The CCC entity starts scanning broadcast messages from other CCC entities and may also start transmitting broadcast messages. These broadcast messages are used for the discovery purposes. In the logical implementation option, the CCC entity in the network registers to the CCC entity in the backhaul. The geo-location area of the network is provided to the backhaul entity in the registration.

In “Discover other networks” phase the CCC entity acquires information of other networks in the area. The CCC entity may regularly enter the discovery phase to discover for example if new networks have started operation in the same geo-location area. If the physical implementation option is used, the CCC evaluates the signal strength and content of the broadcast messages which are received from other CCC entities. In the logical implementation option, the CCC entity requests discovery information from the CCC entity in the backhaul. The CCC entity in the backhaul provides a list of networks which are registered to operate in the same geo-location area. The list contains also information on how to connect to the CCC entities of those networks, e.g. internet protocol address, or address specific to CCC system.

In “Connect to the relevant networks” phase the CCC entity determines with which networks it wishes to share cognitive control information, and creates connection to the CCC entities of those networks. In physical implementation option, the CCC entity responds to the broadcast messages to request connection, and performs the required authentication procedures. Alternatively, the option to broadcast the cognitive control information may be used. This option does not require separate connection creation. The CCC entity start broadcasting cognitive control information if it has discovered other networks supporting the CCC in the discovery phase. However, this option is feasible only if the amount of the cognitive control information is limited, and the cognitive control information can be shared with any networks within the range of the local connectivity technology. In logical implementation option, the CCC entity connects to the CCC entities of the relevant networks using the addressing information provided by CCC entity in the backhaul in the previous phase.

In “Share and receive information with the relevant networks” phase the CCC entity shares and receives cognitive control information over the connections which were created in the previous phase. The connections remain until they are terminated. A CCC entity may actively terminate the connection to another CCC entity if it has determined the connection is no longer needed. The connection may also be terminated passively if no messages have been exchanged before connection timeout.]

###### 6.1.1.1.2 **Main functionalities of the CCC**

In terms of functionality, the CCC may:

1) enable information exchange between independent and/or heterogeneous CRSs which operate in the same area;

2) provide support for coexistence of the CRSs by enabling networks to share information of the network capabilities and characteristics, and spectrum use and;

3) provide support for efficient spectrum use by enabling CRSs to share information about spectrum use, share policies, etiquettes, and spectrum sensing results;

4) enable collaborative spectrum sensing. The networks operating in the same area may agree on a common quite period when they can sense the interferences e.g. from primary spectrum users or other CRSs which are not connected to the CCC. Sharing the sensing results enables a network to gain more, and more reliable, information on the radio environment;

5) provide support for self- configuring networks by enabling CRSs to share and access information about radio environment, use the information to identify optimal spectrum resources, and agree on the spectrum sharing with other networks;

6) provide support for efficient discovery of networks or devices to connect to.

The messages and the protocols to discover other independent and/or heterogeneous networks in the area and to exchange the information with them should be defined.

##### 6.1.1.2 Cognitive Pilot Channel (CPC)

The CPC is a pilot channel (physical or logical) that broadcasts radio environment information intended to aid the decision processes of a cognitive terminal in a dynamic and flexible heterogeneous environment, as also described in [10[E309a]], [29[ET09a]] and [30[ET09b]]. The radio environment information includes information with regard to operators, frequency bands, available RATs, services, and load situation etc. This information can be used to aid a variety of different usage including:

– initial camping[[2]](#footnote-2);

– network association;

– policy distribution;

– simplify inter-system handoffs;

– spectrum brokering;

– pre-emptive access;

– real-time adaptations;

– migration to new standards.

In some proposed radio environment, the cognitive capability of the terminal (or possibly, base station) appears to be a crucial point to enable optimisation of radio resource usage.

Indeed, in order to obtain knowledge of its radio environment, a cognitive radio system may need to obtain information of the parts of the spectrum within the considered operable frequency range of its radio hardware: it is important that this action is reliable and would be carried out within an acceptable time and with acceptable power-consuming performance. On this basis, the CPC concept consists of conveying the necessary information to let the terminal or base station know the status of radio channel occupancy through a kind of common pilot channel.

In addition, the CPC is anticipated to be conveyed by two approaches: the "out-band" CPC and the "in-band" CPC. The first one, out-band CPC, considers that a channel outside the bands assigned to component Radio Access Technologies provides CPC service. The second one, in-band CPC, uses a transmission mechanism (e.g. a logical channel) within the technologies of the heterogeneous radio environment to provide CPC services. Out-band and in-band CPC approaches are considered to be used jointly by broadcasting the general information over out-band CPC and detailed information over in-band CPC. The characteristics of out-band and in-band parts of the CPC are summarized in Table A.7.1.

Taking into account the description of spectrum use database as described in section 6.4.1.3.1, used to store information of spectrum use indicating vacant or occupied frequencies and the rules related to the use of the frequencies in certain locations, the CPC may be used for providing such information to cognitive radio system nodes.

###### 6.1.1.2.1 CPC operation procedure

The typical scenario for application of the CPC in a heterogeneous or multi-RAT context is depicted for out-band and in-band CPC deployment in Figures 13 and 14, respectively. When turned on, the mobile communication terminal or base station may not be aware of which is the most appropriate RAT in that geographic area where it is located, or which frequency ranges the RATs existing in that specific geographic area exploit.

Figure 13

Out-band CPC

The multi RAT environment context



Figure 14

In-band CPC

RAT m

RAT j

RAT k

RAT n

CPC in RAT m

CPC in RAT j

CPC in RAT n

CPC in RAT k

Indeed, in the case where Dynamic Spectrum Allocation (DSA) and Flexible Spectrum Management (FSM) schemes are applied[[3]](#footnote-3), the mobile terminal or base station will have to initiate a communication in a spectrum context which is completely unknown due to dynamic reallocation mechanisms.

In this case, if information about the service areas of deployed RATs within the considered frequency range communicable from a radio terminal is unavailable, it would be necessary to scan the whole frequency range in order to know the spectrum constellation. This may be a power- and time-consuming effort and sometimes the search may not even be effective, as for example in the “hidden-node” case.

In this context, a CPC should provide sufficient information to components of cognitive radio system, including a mobile terminal, so that it can initiate a communication session optimised to time, situation and location. The CPC broadcasts relevant information with regard to frequency bands, RATs, load situation etc. in the terminal location.

In principle, the CPC covers the geographical areas using a cellular approach for out-band deployment. While for in-band deployment case, CPC is carried in system resource, e.g. as an extended system information message on broadcast channel of RATs or other resource partition part. With CPC, information related to the spectrum status in the cell's area is broadcast, such as:

– indication on bands currently assigned to cellular-like and wireless systems; additionally, also pilot/broadcast channel details for different cellular-like and wireless systems could be provided;

– indication on current status of specific bands of spectrum (e.g. used or unused).

The envisaged CPC operation procedure is organized into two main phases, namely the “start-up” phase and the “ongoing” phase:

– For the “start-up” phase: after switching on, the node of cognitive radio systems (e.g. terminal) detects the CPC and optionally could determine its geographical information by making use of some positioning system. The CPC detection will depend on the specific CPC implementation in terms of the physical resources being used. After detecting and synchronizing with the CPC, the node of cognitive radio systems (e.g. terminal) retrieves the CPC information corresponding to the area where it is located, which completes the procedure. Information retrieved by the node of cognitive radio systems (e.g. terminal) is sufficient to initiate a communication session optimised to time, situation and location. In this phase, the CPC broadcasts relevant information with regard to operators, frequency bands, and RATs in this geographical location (e.g. terminal location).

– For the “ongoing” phase: once the terminal is connected to a network or CRS base station is on operation, a periodic check of the information forwarded by the CPC may be useful to rapidly detect changes in the environment due to either variations of the mobile position or network reconfigurations. In this phase, the CPC broadcasts the same information of the “ongoing” phase and additional data, such as services, load situation, etc.

Figure 15 presents the two main phases in the CPC operation taking into account the main steps of the overall CPC operation procedure described above. Both out-band CPC and in-band CPC are jointly used [36[Ch09]] [37[Ch10]].

Figure 15

CPC operation procedure

use of the **Outband CPC**

**Start-up information**

**Ongoing information**

use of the **Inband CPC**

Listen to out-band CPC in order to obtain basic parameters (e.g. available networks at that location)

Select and connect to a network using information from the out-band CPC; stop listening to the out-band CPC

Connect to the in-band CPC within the registered network

Listen to ongoing information using the in-band CPC

To broadcast data allowing a terminal to select a network in an environment where several technologies, possibly provided by several operators, are available

e.g. much more detailed context information, policies for reconfiguration management

###### 6.1.1.2.2 Main functionalities of the CPC

In terms of functionality, the CPC:

1) enables the nodes of cognitive radio system (e.g. mobile terminal to properly select network depending on the specific conditions like for example RATs' operating frequency bands, established policies, desired services, RAT availability, interference conditions, etc.). This provides support to Joint Radio Resource Management (JRRM), enabling a more efficient use of the radio resources;

2) provides support for an efficient use of the radio resource by forwarding radio resource usage policies from the network to the terminals;

3) provides support to reconfigurability by allowing the terminal to identify the most convenient RAT to operate with and to download software modules to reconfigure the terminal capabilities if necessary;

4) provides support to context awareness by helping the terminal identify the specific frequencies, operators and access technologies in a given region without the need to perform long time and energy consuming spectrum scanning procedures;

5) provides support to the network provider to facilitate dynamic changes in the network deployment by informing the terminals about the availability of new RATs/frequencies, thus providing support to dynamic network planning (DNP) and advanced spectrum management (ASM) strategies, providing information of the current status of specific spectrum bands (e.g. used or unused).

By considering such a CPC, the following advantages are pointed out:

– simplifying the RAT selection procedure;

– avoiding a large band scanning, therefore simplifying the terminal implementation (physical layer) for manufacturers;

– the CPC concept seems particularly relevant for the implementation of DSA/FSM;

– the CPC concept as a download channel could be useful to the operator and user in all scenarios where it is necessary to download a new protocol stack to connect to the network.

The deployment of CPC may require information also from the existing technology. The format of the frequency usage information as well as the spectrum band for the CPC needs to be realised in a way that cognitive radio systems are able to access it and understand the information.

###### 6.1.1.2.3 Geography-based implementations of the CPC

There is a need to organize the information delivered over the CPC according to the geographical area where this information applies.

A difference can be made between two options differing on how they provide geographical related information:

− *Mesh-based approach:* The geographical area is divided into small regions, called meshes. In that case the CPC should provide network information for each one of these meshes, being possibly transmitted over a wide area and therefore including a lot of meshes. Initial requirements evaluations seem to conclude that this solution could require a very high amount of bandwidth.

− *Coverage area approach:* In this approach, the coverage area is provided for the different RATs, thus the concept of mesh is not needed any more. For example, the following items could be provided in this approach: operator information, related RATs and for each RAT, corresponding coverage area and frequency band(s) information.

Implementations of these two approaches are given in Annex A.7.

* + - 1. Challenges to further development of CPC and CCC

Some challenges arise when considering listening to a wireless channel for obtaining knowledge of the operational environment.

Various sources in literature have proposed the use of a predetermined common coordination channel for spectrum etiquette, network establishment and adaptation to changing interference environments, see [23[JR07] , 24[E309c], 25[KP09]]. Local coordination and sharing of information provides low delay and accurate sharing limited to the involved networks.

The CCC usage may increase the power consumption of the devices. The power consumption should be considered carefully and particularly if the nodes are mobile. In such case the challenges related to the power consumption are to limit the signalling overhead and to enable efficient power save mode which still enables low latency information sharing. Thus, it is important to find the optimal amount of shared information and the latency for the information sharing. In addition, in the case the nodes have to connect over the internet, the appropriate network access to be used should be selected.

Further challenges of CCC such as the synchronization between the involved nodes, the contention resolution mechanisms when accessing the spectrum, and the reliability of the exchanged information should be investigated.

According to [12[E309b]], the CPC concept could provide the necessary support for obtaining knowledge of the spectrum occupancy. However, also the use of CPC would require further investigations on some technical challenges before being considered as a mature approach, such as: the CPC delivery should strictly satisfy the timing requirements coming from the opportunistic spectrum use; the CPC content should be updated in a proper timeframe, according to the one related to opportunistic spectrum use.

Setting arise on the above consideration, it can be concluded that further research and development in order to improve the maturity of both CCC and CPC are needed e.g. in ETSI RRS and IEEE 802.19.1. For this purpose a feasibility study on different approaches and implementation options of control channels for cognitive radio systems is carried out in the scope of [ET11].

#### 6.1.2 Spectrum sensing

Sensing is a capability to detect other signals around the CRS node. It is usable in particular in cases where the level of the detected signal is sufficiently strong, and/or the signal type/form is known beforehand.

A lot or research is focusing on sensing techniques, and there are also a number of sensing methods.

##### 6.1.2.1 Sensing methods

Obtaining knowledge of the radio environment, including spectrum use is among the vital information for a cognitive radio system to realize its functionality.

Currently different spectrum sensing methods are considered for cognitive radio systems. These methods include energy detection, matched filtering, cyclostationary detection and wavelet based detection etc. These existing sensing methods differ in their sensing capabilities and also their computational complexities. The choice of a particular sensing method can be made depending on sensing requirements, available resource such as power, computational resource and application/signal to be sensed.

Performance indicators which are related to the impact of different spectrum sensing techniques to other users of the spectrum include e.g. the following:

– Detection threshold for the signals of the existing system.

The minimal signal-to-noise ratio which is needed by each spectrum sensing method in various existing systems to achieve a certain probability of detection.

– Detection time for the signals of the existing system

The duration which is used by each spectrum sensing method to detect the signals of existing system.

– Detection probability

Probability that the signal is correctly detected when it is present

– False alarm probability

Probability that the signal is detected when it is not present.

– Time between failures in detection

Average time period between failures in signal detection (i.e. signal is not detected when it is present)

– The lost spectrum opportunity ratio

The expected fraction of the OFF state (i.e., idle time) undetected by CR users.

– The interference ratio

– The expected fraction of the ON state (i.e., the transmission time of the networks of the existing systems) interrupted by the transmission of CR users.Matched filter detection.

The optimal detector in stationary Gaussian noise is the matched filter since it maximizes the received SNR. The main advantage of matched filtering is the short convergence time to achieve a certain probability of misdetection or false alarm. However, the problem with this approach is that the perfect prior information of the signal to be detected (modulation type, order, pulse shape and packet format, etc.) is needed. Radio networks with pilot, preambles and synchronization words and spreading codes can use this matched filter detection. Since cognitive radio system needs receivers for several different signal types, the implementation complexity of sensing unit is impractically large and various receiver algorithms also lead to large power consumption. The matched filter is also not suitable for spectrum sensing in very low SNR regions since synchronization is difficult to achieve [26 [YA09]].

Energy detection

If there is no information of the primary user signals to be detected, the optimal detection is an energy detector. Its generic nature as well as low computational and implementation complexity are attractive features for this scenario. The energy detector simply measures the energy of the received signals and compares it to a threshold which depends on the noise floor. However, the problem with the energy detection is that the noise floor might be unknown to the detector, thus, finding a proper threshold is challenging though training can be done with pilot signals. Because the energy detector is unable to distinguish between noise and interference from primary user false detection might be triggered by unintended signals. The energy detector does not perform well in low SNR regions or in detecting spread spectrum signals [26[YA09]]. One method for using information from the energy detector is noise floor based method where the receiver measures the cumulative RF energy from multiple transmissions over a particular frequency spectrum and set a maximum cap on their aggregate level. As long as a cognitive radio node does not exceed this limit by their transmissions, it can use that frequency spectrum.

Cyclostationary property detection

This type of detector operates based on the cyclostationary property of the signals. Cyclostationary features are caused by the periodicity in the signal or in its statistics like mean and autocorrelation or they can be intentionally induced to assist spectrum sensing. Cyclostationary property detector can differentiate between noise and primary users signal because noise has no correlation. It can also classify different types of transmission and primary users [26[YA09]]. It performs better than the energy detection in terms of probability of detection particularly in low SNR region. However, the computation complexity is relatively high and it also requires longer sensing time than energy detector[27[Ca06]]. For more efficient detection, the cyclostationary property can be combined with pattern recognition based on neural networks.

Self-correlation detection

In self-correlation detection, the decision statistic for the binary hypothesis is derived from signal autocorrelation sequence instead of the received signal itself. The correlation lag/delay is chosen in accordance with the maximum bandwidth of the signal involved. The decision statistic is obtained after converting the correlation sequence to frequency domain through FFT. The scheme improves the probability of detection compared to the energy detection in the presence of noise power uncertainty with less complexity compared to cyclostationary property detection. However, if multiple primary users are present, unwanted signal due to the non-linearity of the correlation operation arises. This would affect the performance especially if the primary users are many and have weak signals.

Waveform based detection

Known patterns, for example, preambles, mid-ambles, regularly transmitted pilot pattern, spreading sequences, are usually operated in wireless systems to assist synchronization or for other purposes. In the presence of a known pattern, waveform based detection can be performed by correlating the

received signal with a known copy of itself. Compared with energy detection, this method requires shorter measurements time and outperforms in reliability. Furthermore, the performance of the sensing algorithm increases as the length of the known signal pattern increases[26[YA09]].

Distributed sensing

Distributed sensing system has been employed in the past for both commercial and military services. Here, the focus is in the context of radio spectrum sensing. Due to multiple factors like noise and interference, shadowing, fading and limitation of the sensing method, it may be very difficult to use a single standalone sensor to obtain high quality of sensing. In this case, distributed sensing can be used where each individual sensor can either be located inside or outside the cognitive node. As the name implies, the spectrum sensing is executed using multiple sensors distributed spatially. These distributed sensors have the ability to exchange sensing information, making decisions and relay the sensing information to the cognitive radio system nodes. The sensing information is supplied to the cognitive node in a cooperative manner where the data from all sensors is aggregated to obtain the final sensing information. Such implementation method can dramatically improve the sensing quality of the cognitive radio system. This would relax the sensing requirements and choice of the sensing method at each sensor. Note, however, that relaying the sensing information requires a channel free from primary users.

MAC-layer spectrum sensing

In cognitive radio networks, the available channels for cognitive radio users are dynamic, so reservation channels ahead of scheduling seems unfeasible in cognitive radio environment.   
For the varying state of channel occupation, MAC-layer sensing algorithm can be utilized to help the secondary user to find an idle channel to access quickly and find an idle channel with the lower channel handoff probability. As a result, the spectrum utilization efficiency can be improved by using MAC-layer sensing algorithms.

Moreover, MAC-layer sensing algorithms may be combined with channel allocation to achieve efficient dynamic spectrum allocation. Also, considering the constrained energy and limited processing capacity of mobile users in CRS, sensing interval could be adjusted.

The cognitive radio network obtains channel-usage characteristic with such spectrum sensing method and stores the information (e.g. channel state, occupancy duration, vacancy duration, probabilities of the occupancy and vacancy duration). By using the stored information, sensing interval will be adjusted according to a certain policy [40[Ch13]].

The traditional MAC-layer sensing algorithms include Channel Utilization Ascending Order (CUAO) MAC-layer sensing algorithm, Random Order (RO) MAC-Layer spectrum sensing algorithm, and Channel Opportunity Quality Descending Order (COQDO) MAC-Layer spectrum sensing algorithm.

The RO MAC-Layer spectrum sensing algorithm searches for an idle channel in random order. CUAO MAC-layer sensing algorithm [41[Ch14]] searches for an idle channel in ascending order of channel utilization. The channel utilization of different channels can be obtained from periodically‑collected statistical information through spectrum sensing. COQDO MAC-Layer spectrum sensing algorithms first determine the channel opportunity quality (COQ) by considering both the channel utilization and the channel state transition from idle to busy; where the channel utilization and channel state transition from idle to busy of different channels can be obtained from periodically-collected statistical information through spectrum sensing [43[Ch16]], and then searches an idle channel according to the descending order of the channel opportunity quality (COQ).

Multi-antenna spectrum sensing

Compared with single antenna spectrum sensing, multi-antenna spectrum sensing can obtain time diversity gain and space diversity gain. Thus, under given detection and false alarm probabilities, the multi-antenna spectrum sensing outperforms the single antenna spectrum sensing. The multi‑antenna spectrum sensing can be divided into two categories, namely space diversity based multi‑antenna spectrum sensing and space-time diversity based multi-antenna spectrum sensing, respectively. Eigen value is commonly exploited for both categories. The eigenvalue-based spectrum sensing methods can be combined with subspace techniques to meet the stringent low SNR requirement and also mitigate adjacent channel interference.

Edge detection for wideband spectrum sensing [44[Ch17]]

In some cases, CRS may identify used spectrum over wide frequency bands. For spectrum sensing over wideband channels, the edge detection approach offers advantages in terms of both implementation cost and flexibility in adapting to the dynamic spectrum, as opposed to the conventional use of multiple narrow-band bandpass filters. The edge detection techniques can be used to effectively detect the channel borders in power spectrum density (PSD). Therefore, the edge detection techniques for wideband spectrum sensing can effectively scan over a wide bandwidth to simultaneously identify all subbands, without prior knowledge on the number of subbands within the frequency range of interest.

##### 6.1.2.2 Challenges of spectrum sensing

*[Editor’s note: Develop the proper Definition of Hidden Node Problem. It should be noted that the definition of “hidden node problem” has already developed in CRS1 Report. Consistency is needed.]*

Some challenges arise when considering spectrum sensing for obtaining knowledge of the operational environment. One of them is the hidden node problem. [Hidden node problem means that……….]

Furthermore, spectrum sensing requires high sensitivity, sampling rate, resolution analogue to digital (A/D) converters with large dynamic range, and high speed signal processors. When wideband sensing is considered terminals are required to capture and analyze a wide band, which imposes additional requirements on the radio frequency (RF) components. Wideband sensing also means that a wide range of signals with different characteristics needs to be detected which adds to the complexity of sensing since it needs to adapt to e.g. different energy levels or cyclostationary features of the primary signal [26[YA09]].

Therefore it might be useful to utilize sensing technologies in a limited frequency range in which the range of technologies used by the other existing systems in the band is limited [29[RS10]].

It should also be noticed that if sensing is to be used in a band where there is a need to sense several different signals, and this requires implementation of several sensing technologies in a device, the complexity and cost of the devices will rise.

An important issue that has to be considered is the reliability of sensing, that is how much reliable is the information obtained sensing the spectrum. Indeed, in case of unreliable information, there could be consequences for the primary system (and even for the secondary system). Several recent studies and statements as the ones reported in [23 [Ne09]], [25[LC10]], [26[GS08]], [[27], [28[EC59]] and [31[FC10]], show that the reliability of sensing is one of the most critical challenge to spectrum sensing.

[12[E309b]] reports a study focused on the reliability of a spectrum sensing technique as a way to obtain the knowledge of the 2G system spectrum occupancy. As a result of the study, it is possible to conclude that the considered spectrum sensing techniques may suffer of a very low reliability in the evaluation of the spectrum occupancy and this aspect could be really critical in an opportunistic spectrum use context as decisions should be made in a strict timeframe. Similar results are also reported in [25[LC10]], where it is concluded that the dependence of the perceived spectral activity with the user location along with the presence of external noise sources (e.g. man-made noise sources like AC power systems, electric motors, etc.) altering the observed spectrum occupancy suggest the need for sophisticated spectrum sensing methods as well as some additional techniques in order to guarantee an accurate spectrum occupancy detection.

Thus, it does appear clear that the implementation of opportunistic spectrum access mechanisms could not rely simply on the spectrum sensing techniques, in particular in case of terminal-side only approaches. Indeed, when exploiting spectrum sensing in case of failure to obtain knowledge or in case of unreliable information of radio environment, CRS using spectrum sensing approach needs to have alternative methods to cope with the situation.

In [28[EC59]] it is stated that sensing is not a preferred solution to protect the broadcast service in the UHF TV bands and that the potential benefit of using sensing in addition to the geo-location database needs to be further considered. When sensing is implemented, testing procedures would need to be developed by standardization bodies to assess the efficiency and the reliability of the sensing process / device. In addition, to protect emerging systems of the broadcast service, sensing algorithm would require continuous developments, which may raise legacy issues Research on sensing [23 [SK10]] has shown that PMSE services can be very difficult to detect under realistic conditions, even by cooperative sensing..

When spectrum is used opportunistically, the primary system has the priority to use its frequency bands anytime. Therefore, cognitive radio systems should be able to identify the presence of primary user and vacate the band as required within a certain time depending on the requirements of the specific primary user. For example if the cognitive radio system is exploiting opportunities at the public safety band, there may be a sudden need for more spectrum by the primary use, the tolerance time will be very small and if the opportunistic spectrum use is based on sensing, it needs to be done frequently. Also the temporal characteristics of the primary user affect how frequently the sensing should be done. For example the presence of a TV station does not usually change frequently in a geographical area, but the use of wireless microphones may change rapidly [25[KP09]].

It can occur that the primary user receiver is in the transmission range of the cognitive radio system but the primary user transmitter is not. This could be the case e.g. with wireless microphones. There are also receive-only users, such as passive radio astronomy services which cannot be detected by sensing [26[YA09]] [29[RS10]].

In addition to the challenges reported above, in general, also the following ones should be addressed while investigating the sensing approach:

– Algorithm complexity may be related with power and processing consumptions.

– The complexity of each spectrum sensing method (in terms of power and processing consumptions) related to the observed bandwidth.

– Sensing signalling cost (e.g. including cost in sensing measurement and sensing reporting).

– For cooperative sensing, signalling cost in the combination of the sensing reports should also be included as well as synchronization issues.

Based on the current studies that have been referred, the sensing techniques are not mature enough and further research effort is needed on spectrum sensingin order to understand how such a technique can be implemented and what would be the sensing requirements in each band and with relevant primary services.

### 6.1.3 Databases

#### 6.1.3.1 Geolocation and access to databases

*[Editor’s note: This section needs reshaping by changing the order of the paragraphs. (geo-location part and database access.]*

The objective of databases is to provide information about the locally usable frequencies and thus to provide protection to incumbent services from harmful interference. The database can protect a wide range of radio services, including passive services which cannot be covered by sensing.

Databases can deliver information of vacant spectrum and the rules related to the use of those frequencies in certain locations, such as information on the allowed maximum transmit power. By knowing the locations and having access to the database, the cognitive radio devices can check available frequencies from the database to be used for their own transmissions. The information on the database can be obtained either by the CRS itself or the information can be provided by another system (passive awareness [4 (FK07)]).Database approach is especially useful to protect primary usage where the locations of the stations are known and remain stable and spectrum use does not change frequently[29[RS10]].

Several approaches to databases can be possible. The approach can vary e.g. on the time frame on which the information on the spectrum is gathered. Short term database can be used to indicate vacant frequencies at a given moment. Long term databases on the other hand can be used to gather the spectrum usage information from a longer period and the information can be used e.g. predicting the future usage of the spectrum and learning [30[HV10]].

For example on UHF TV bands, as stated in [31[FC10]], the geo-location and database access method provide adequate and reliable protection for broadcast services, so that spectrum sensing is not necessary. For example, the Cognitive Pilot Channel (CPC) described above in section 6.4.1.1.2 could be also used for providing the information contained in the database to cognitive radio system nodes.

Any database could contain and utilize information on all services the administrations want to protect in the bands to be accessed by the CRS devices. This could include information on protected receive sites or operational areas of those protected services, as well as on any registered devices.

The operation of the database can also be organized in different ways, and there are several proposed architectures. [32[EC10]]

It is possible to have one or more databases and they could be provided by the regulator or third parties authorized by the Regulator. If there are multiple databases they all need to provide the same minimum information about the available frequencies to the cognitive device.

• Single open database: One option is to have a single database for the entire country or for a region. All cognitive devices consult this database using a pre-defined and standardized message format. The database would be open to all users. In practice a regional database may not be practical due to differences in national approaches.

• Multiple open databases: A second option is to have multiple databases. In this case, cognitive devices could select their preferred database but there would be no difference between them in the information related to the allowed frequencies. One benefit could be an improved availability as a result of the redundancy of databases. In addition, if some of the databases are operated by third parties, they could offer also other information and value-added services to the cognitive devices, in addition to the mandatory interference protection related information.

• Proprietary closed databases: A third option is to have “closed” databases corresponding to different types of devices. For example, a manufacturer of cognitive devices might also establish a database for those devices it had made. Multiple manufacturers might work together to share a single closed database or one manufacturer might “open up” its protocols and database for others to use if they wish.

• ‘Clearinghouse’ model: The ‘clearing house’ model partitions the process of providing information on available channels to CRS devices, in order to facilitate the development of multiple database service providers. The key element is the clearing house, which aggregates and hosts the raw data needed to perform database calculations. Since there would be only one of these per country or region, it would need to be carefully regulated to ensure equitable access conditions as well as integrity of data handling and distribution.

Open interfaces and protocols should be defined between the devices and the database so that different types of CRS devices can access a database-based on those interfaces and protocols.

There are several ways to implement the geo-location. Fixed CRS devices such as access points can be professionally installed and their location then programmed into the device. Personal computers and other portable devices can use geo-location technologies such as GPS chips. Also triangulation using radio towers or any other location determination method provided those methods provide sufficient accuracy to determine the location of devices at a given point and time. Once the device knows its location, or it is determined by the access point acting as a master device, it can be communicated to the database to determine the frequencies available for use in its area [32].

#### 6.1.3.2 Multi-dimension cognitive database [39[Ch12]]

An important characteristic of CRS is its capability of making decisions and adaptations based on past experience, on current operational conditions, and also possibly on future behavior predictions. An underlying aspect of this concept is that CRS must efficiently represent, store and manage environmental and operational information.

Cognitive database is a promising module in CRS architecture by storing and managing cognitive information to support the functions implemented in cognitive circle. This database is a logical entity which can be organized flexibly in both centralized and distributed manner.

The cognitive information in cognitive radio systems is comprehensive, including information of space, time, frequency, user, network and different layers of system. The cognitive database should be divided into several dimensions in terms of its nature, and the cognitive information in which should be managed based on the dimension division, such as

– Radio dimension

• Parameters of radio transmission characteristics

– Network dimension

• Information reflecting the network status

– User dimension

• Information related to users or concerned by users

– Policy dimension

• Guideline of radio resource management, spectrum policies, operator policies

#### 6.1.3.3 Challenges of geo-location/database

Cognitive radio devices may need to be capable of knowing their locations and accessing the database. Using databases to present fast varying spectrum use is challenging as the information stored in the database can become outdated fast.

Furthermore, database approach may not be suitable in cases where the location of the protected stations is not known or they cannot be registered in the database.

The management of database includes also security and privacy aspects that need to be considered.

The sensitivity of the information stored in the database could be very high, and should be carefully managed in the network, in order to avoid any unauthorized or unexpected access the data. As a basic principle for addressing the security of the information, two categories of information could be introduced: a first category related to non-sensitive information, and a second category related to sensitive information. Any information related to the available RATs and related frequency bands in a certain area should be included in the first category, since this kind of information need to be sent freely to any mobile device. On the other side, any information related to some specific actions, decisions and operations in the networks should be included in the second category.

The information that the database provides to the devices may depend on the regulation and the database implementation. The CRS may be able to operate in various countries and frequency bands, and thus it may need to access to various databases. For providing global interoperability for CRS, a unified and flexible interface, which enables access to various databases globally, should be defined. Such interface may be defined e.g. in IETF PAWS[[4]](#footnote-4).

## 6.2 Decision making and adjustment of operational parameters and protocols

*[Editor’s note: It is difficult to approach the different solutions below without further details on the actual problems to be solved. More clarity is required.]*

The design of future cognitive radio systems will face new challenges as compared to traditional wireless systems. Future cognitive radio systems need take into account the underlying policies in the different spectrum bands that determine the rules for using the bands and transform the policies into adjustment actions. The operational environment will be heterogeneous consisting of several radio access technologies with diverse sets of terminals to support a wide range of services. In addition, the operational environment will be more dynamic as the number of users and the applications they are requesting vary in time leading to changing requirements for resource management. As a result the resource management in a dynamic and complex environment becomes a multivariable optimisation problem with conflicting requirements where optimal solutions are difficult to find.

The decision making in cognitive radio systems can be done with mathematical or heuristic methods. Mathematical algorithms have good performance and reliability, but they can be complex and their applicability depends on the characteristics of the target system. In dynamic environment mathematical models may not be suitable for the target problem leading to performance degradations. Heuristic methods could be based on mathematical understanding and statistical knowledge, human-kind thinking or artificial intelligence (AI) applied to problem to solve. Techniques like rule-based expert systems, fuzzy logic, neural networks, genetic algorithms, or

combinations of them may be attractive to tackle problems that hinder using mathematical algorithms. With heuristic methods the decision making system can be designed to handle such unusual, or even unpredictable, cases that are difficult to implement using mathematical methods.

### 6.2.1 Decision making method

#### 6.2.1.1 Centralized decision making

A simple architecture to support the dynamic adaptation of the operational parameters in CRS is to have a centralized entity for decision making, which could coordinate the operational parameters and resources and consequently realize and issue decisions for utilizing the spectrum resources or channels.

The central entity obtains the knowledge of its radio operational and geographical environment, its internal state and the established policies, and monitors spectrum usage patterns and users’ needs, for instance, by sensing the spectrum use, using a database and/ or receiving control and management information through listening to a wireless channel, e.g. the cognitive pilot channel (CPC) or cognitive control channel (CCC). Based on all obtained information, the central entity makes a decision on the adaptations of its operational parameters including e.g. spectrum resources to CRS users in the area it manages.

The centralized architecture is simple and easy to control from the operator’s view. However, when the amount of components increases greatly, a single centralized entity would not be able to cope with the coordination, decisions making and management for hundreds/thousands of cognitive radio networks resources. This will not only lead to scalability issues, but will also introduce significant delays in the resource management decisions being conveyed. Besides, the centralized entity may not be easy to collect dynamic information from all involved network entities and make fast decision.

#### 6.2.1.2 Distributed decision making

A distributed approach is based on localized decisions of distributed network entities. Distributed decision making approach could be used when a set of ad hoc cognitive radio systemsoperating in the same area, and in the same frequency band using dynamic access. In this case, each CRS node would have to gather, exchange, and process the information about the wireless environment independently. The decisions on the actions would be carried autonomously based on the available information.

The delay is substantially shorter to facilitate dynamic change of situations when compared with centralized approach. However, there may be an issue with stability (especially when entities act independently without coordination) as it is difficult to prove that the proposed solution will always behave in a predictable manner.

A cognitive radio node can adopt to either cooperative or non-cooperative behaviour. Cooperative cognitive radio node will make a decision on e.g. spectrum access to achieve the best overall performance of the network whereas a non-cooperative user will make a decision only to maximize its own benefits. In a distributed approach nodes have to collect the information themselves. If information is collected non-collaboratively, all network information is gathered and processed locally by each of the nodes without interaction amongst them. If nodes collaborate, they can exchange network information with each other, e.g. over CCC. The reliability of the information increases in the cooperative approach because it is collected from multiple sources. Because exchanging network information consumes network resources and, depending on the collaboration means, may degrade transmission performance, a user may not collaborate with other users if the benefits to be gained are not considerable.

The non-cooperative cognitive radio nodes that do not collaborate with other nodes for information exchange can make the decision independently by choosing the actions that optimize their own performance while fulfilling the given constraints arising e.g. from policies. If the nodes decide independently e.g. their channel and power allocations, the overall performance of the network in terms of e.g. throughput may not be good. With cooperation between the nodes, the actions can be optimized to obtain better overall network performance. The nodes can collaborate using e.g. control channels or databases to optimize the operation of the network instead of a single node. There is a wide range of techniques for distributed decision making including e.g. game theory, metaheuristics (e.g. genetic and search algorithms), Bayesian networks and neural networks. Different decision making techniques are more suitable in different scenarios depending on the operational environment, network conditions and cooperative/non-cooperative and collaborative/non-collaborative behaviour.

The trade-off between the centralised v/s distributed should be studied case by case. Sometimes hybrid solution may bridge the gap between the two extremes [33[HN09]].

#### 6.2.1.3 Examples of possible criteria to be used for dynamic spectrum access

##### 6.2.1.3.1 Frequency channel selection

The cognitive radio system may be able to recognize the utilization probability of different frequency channels, the state transition probability from idle to busy of different channels, the usage model of different channels from periodically-collected statistical information though out-of-band and in-band spectrum sensing. In order to select most suitable channel that improves the utilization of available spectrum, the cognitive radio system needs to identify the opportunity utilization quality of the different channels by integrally considering the information obtained by the cognitive radio systems. The considered information could include e.g. the following aspects:

1) utilization of channel probability;

2) state transition probabilityfrom idle to busy of channels;

3) the usage model of different channels;

4) traffic pattern in different channels;

5) bandwidth as well as traffic requirements of the cognitive radio users;

6) channel collision problem for the scenario of multi-cognitive radio users.

##### 6.2.1.3.2 Frequency channel handover

Frequency channel handover occurs when a CRS user changes frequency e.g. in case the frequency is reclaimed or, due to the channel conditions, the communication can not be maintained. Frequency channel handover may cause delay and packet loss to the CRS user. Frequency channel handover strategy is trying i) to maintain the seamless connectivity of CRS users and ii) to guarantee the QoS requirements of the CRS user.

The considered information may include e.g. the following aspects:

1) usage model of different channels;

2) predicted vacant time of channels;

3) quality of channels, such as SNR and path loss;

4) bandwidth as well as traffic requirements of the cognitive radio users;

5) handover delay.

### 6.2.2 Adjustment methods

*[Editor’s note: The relationship between “the adjustment of operational parameters and RBS management” is described here. Short introduction is needed. Further contribution is needed.]*

#### 6.2.2.1 Reconfigurable base station (RBS) management

The availability of reconfigurable nodes in the networks (i.e. nodes whose hardware and processing resources can be reconfigured in order to be used with different RATs, frequencies, channels, etc.) will give the network operators the means for managing in a globally efficient way the radio and processing resource pool, with the aim to adapt the network itself to the dynamic variations of the traffic offered to the deployed RATs and to the different portions of the area. In addition, possible OPEX and CAPEX reduction could be obtained in network deployment and operation. As a matter of fact this technology could also have an impact on the current planning processes.

As an example of self-adaptation on the basis of traffic load, it could be considered to deploy RAT1 and RAT2 systems in a geographical area with a network built with reconfigurable base stations, thus having reconfigurable hardware shared between RAT1 and RAT2 functionalities. During the daily life of the network, it could be needed, for instance due to different traffic loads on the two RATs, to increase the percentage of processing resources devoted to the over-loaded system while decreasing the resources given to the other (supposed under-loaded). In Figure 15, a reconfiguration example increasing RAT2 resources is depicted.

Figure 15

Reconfiguration example

##### 

An example of possible network architecture to enable the aforesaid traffic handling mechanism is reported in Figure 16.

This architecture constitutes of reconfigurable base stations, whose hardware and processing resources can be reconfigured in order to be used with different RATs, frequencies, channels, etc.

In particular, the architecture foresees common radio control functionalities for the different access networks of each RAT and one or more reconfigurable base station BS*1*, …, BS*k*. Each base station (BS1, …, BS*k*) is a multi-RAT base station, and able to manage different systems at the same time and to be reconfigured accordingly, and includes hardware/software reconfigurable transceiver modules.

Inside any multi-RAT reconfigurable base station, each supported cell has its own reconfigurable hardware pool, shared among supported RATs.

In addition, each reconfigurable base station BS*1*, …, BS*k* can be reconfigured in terms of percentage of processing resources devoted to each supported RAT and in terms of active radio resources (e.g. frequency carriers) for each supported RAT.

Figure 16

Reference network architecture

**Reconfiguration Management**

**RRM**

**Radio Control functionalities**

**Base station *k***

**Base station *i***

Reconfigurable Hardware (HW)

The radio control functionalities include the Radio Resource Management (RRM) entity which aim is to manage the request and the assignment of a radio channel to the mobile terminals that are in the cells managed by the base station BS*1*, …, BS*k*. In the reference architecture depicted above a new functionality called Reconfiguration Management has been introduced, in order to run the reconfiguration algorithm. This functionality is devoted to:

− monitor periodically the current activity status of the cells (for each supported RAT) in terms of measurement of the number of the requests and rejects (if any) from the different systems;

− execute the reconfiguration algorithm that decides which base station(s) are to be reconfigured;

− control the reconfiguration by sending appropriate reconfiguration commands (according to the algorithm output) to the base stations in order to reconfigure them.

It is worth noting that the reconfiguration management could also be placed inside a core network or Operation & Maintenance (O&M) node or even inside each node (e.g. in case of flat-architecture) supposing that it can opportunely interact with RRM and reconfigurable base stations entities.

The reconfiguration algorithm determines which base station(s) has(have) to be reconfigured, with the aim to adapt the percentages of processing resources devoted to each supported RAT and to dynamically shape the active radio resources to the behaviour of the traffic.

Thus, the Reconfiguration Management commands the processing resource reconfiguration to the base station(s) through the appropriate interface with each base station BS*k*.

New protocol messages bearing the information to the base station for the appropriate reconfiguration action (e.g. processing resources and radio resources - such as frequency carriers - to activate/deactivate for each supported RAT) could be introduced.

The process described above is then repeated for each base station involved in the reconfiguration process.

#### 6.2.2.2 Method of adjustment based on SOR architecture reconfiguration

SOR (Service-Oriented Radio) architecture is an implementation method of introducing service‑oriented idea into radio communication system. In SOR, various reconfigurable CRS function modules, not only including software process modules but also including hardware process modules, are provided in service manner and deploy distributely in LAN or Internet. All kinds of applications of CRS are implemented by service’s scheduling and invocation. CRS based on SOR may have the following advantages: loosely coupled architecture can enhance system flexibility and business agility; reusable services can reduce deployment scale of the infrastructure and the operator’s costs. The reconfiguration of CRS can be realized flexibly through combining services and/or changing services parameters. Detail information is provided in Annex A.8.

## 6.3 Learning

Learning can enable performance improvement for the cognitive radio system by using stored information both of its own actions and the results of these actions and the actions of other users to aid the decision making process. The learning process creates and maintains knowledge base where the data is stored.

Learning techniques can be classified into three major learning schemes such as supervised learning, unsupervised learning, and reinforcement learning. Supervised learning is a technique which uses pairs of input signals and known outputs as training data so that a function that maps inputs to desired outputs can be generated. Case-based reasoning is an example of supervised learning technique where the knowledge base contains cases that are representations of past experiences and their outcomes. Reinforcement learning uses observations from the environment in learning. Every action has an impact in the environment and this feedback is used in guiding the learning algorithm. Q-learning is an example of this class. Unsupervised learning techniques aim at determining how the data are organized. Clustering is an example of unsupervised learning technique [34[DH01]]. Also aspects of “game theory” and “policy engines” are among the techniques under investigation for CRS management[[5]](#footnote-5).

Major learning schemes can include several specific learning techniques such as genetic algorithms, neural networks, pattern recognition, and feature extraction. Neural networks provide a powerful tool for building classifiers. Pattern recognition and classification can be seen as crucial parts of an intelligent system that aims at observing its operating environment and acting based on observations. Feature extraction and classification are complementary functions. A very important task is to find good distinguishing features to make classifier perform efficiently.

Learning makes the operation of cognitive radios more efficient compared to the case where only information available at the design time is possible. For example, learning enables use of traffic pattern recognition. A cognitive radio system can learn the traffic patterns in different channels over time and use this information to predict idle times in the future. This helps to find channels offering long idle times for secondary use, increasing throughput for secondary users and simultaneously decreasing collisions with primary users. Moreover, a CRS could also be able to recognize the type of the application generating the traffic by looking at the statistical features of the traffic. This would help the management of the network since different applications have different QoS requirements, e.g., VoIP and media downloading.

Learning helps also in fault tolerance since patterns of faults can be identified as logical sets that can be interconnected as a constraint network or a reactive pattern matching algorithm. This approach can enable a more efficient fault isolation technique as it identifies multiple potential causes concurrently and then chooses the most likely based on precedence and weighting factors.

A major challenge in learning is the maintenance of knowledge base which is a key requirement for efficient learning and reasoning. The knowledge base should be able to adapt to the possible changes in the environment to offer relevant information to the decision making. The size of the knowledge base is not allowed to grow uncontrollably. Rather the size should remain at the reasonable level. Thus, an administrative component might be needed in the system to take care of these tasks. All the unnecessary information should be taken away from the database on a regular basis. Administrative component might be also needed to restrict the amount of changes in the knowledge base to avoid chaotic situations. Moreover, the knowledge base could be tailored to operate efficiently with the specific learning techniques used in the system [6 [Ma07]] [35[CH07]].

# 7 Coexistence

## 7.1 Coexistence approaches

*[Editor’s note: Coexistence approaches which are described in Sections 7.1.1 and 7.1.2 should be clearly defined. Contribution is needed to provide a clear text defining these terms at the next meeting.]*

[With regard to CRS, two coexistence approaches are identified:

– coexistence with [non-CRS /other radio systems] ([Vertical coexistence]);

– coexistence between CRSs ([Horizontal coexistence]).

## 7.1.1 [Coexistence with [non-CRS /other radio systems] (Vertical coexistence)

[This coexistence approach refers to the CRS deployment scenario described in section 6.1.4 (examples 1 and 2), and is based on an approach where a mechanism using cognitive radio capabilities is used to identify unused portions of spectrum [of radiocommunication allocations/of radio systems other than CRS]/of another radio system/in a shared frequency band] and to utilize those portions of spectrum without causing any harmful interference[ to systems deployed according to these allocations/to radio systems other than CRS/ to the other radio systems.]

This type of coexistence can be called vertical coexistence where the basis is the opportunistic spectrum access. An example of such scenario is the use of White Spaces in the UHF TV bands.

Examples: 5 GHz RLAN (using DFS), UWB (using DAA) and the use of white spaces in the UHF band (using geo-location and accessing to database).]

### 7.1.2 [Coexistence between CRSs (Horizontal coexistence)]

[This coexistence scenario addresses the CRS deployment scenario described in section 6.1.1, 6.1.3 and 6.1.4 (example 3), and is based on an approach where cognitive radio systems may access the spectrum equally. This type of coexistence is called as horizontal sharing [21[Mu10],22].

In this model specific available portions of the spectrum may be identified to collective use [22 [ET09a] which allows a number of CRSs to access these specific portions of spectrum at same time in a particular geographic area under a well defined set of conditions. And these specific portions of the spectrum have usage restrictions to ensure coexistence with the other users. Conditions of access for the collective use in the band may require the devices to have cognitive features to facilitate coexistence with primary user or between CRSs.

The coexisting Cognitive Radio Systems may use same or different RATs. In the case of CRSs using the same RAT, the CRSs may use coexistence mechanisms that are defined within this RAT. This kind of coexistence mechanisms can be called as self-coexistence mechanism. In the case of CRSs using different RATs, additional mechanisms enabling coexistence may be required. In addition, they may employ CRS features to become aware of each other and capable to use the spectrum in mutually useful manner. Such features are called as cross-coexistence mechanism.

There could be a need to establish policies in order to ensure that various applications could use the frequency band on a non-discriminatory basis based on their technical capabilities. The policies provision should consider ensuring fairness and effectiveness, and in addition, take into account other aspects e.g. load balance between systems, etc. In this approach, cognitive features are used to dynamically use the spectrum with each other in such a way that all devices have the same rights and an equal chance to access the spectrum, i.e. the cognitive features are used to ensure a fair distribution of rights to access the spectrum.

Examples: This type of coexistence can be typically used in ad hoc networks. Each device that is added to the network results in a reconfiguration of the network to fairly distribute the resources.]]

## 7.2 Technical solutions for CRSs to ensure coexistence

There are a number of technical solutions that could be used to facilitate the coexistence approaches described above.

This section provides several examples of such technical solutions. These and other technical solution for coexistence are subject to study before they can be implemented.

### 7.2.1 Geolocation capability coupled with database access

This approach involves geo-location capable CRS nodes accessing a database to obtain information related to the coverage area of the CRS node to facilitate coexistence. This approach can be applied to both coexistence approaches.

When a CRS node is checking for available spectrum it will access database for information on frequency bands that are not currently used by other radio systems, thus can be available at the location of the CRS node.

[When several CRS nodes aim to check for coexistence with each other, the database could further facilitate discovery of these CRS nodes by each other and assist in providing information required for coexistence between these CRSs.]

### 7.2.2 Wireless Control Channel or beacon signal

[*Editor’s note: The three items; CCC, CPC and Beacon should be described at the same description level. Contribution is required for the text of beacon. Introductory section for Beacon should be created. The definition of Beacon should be included in the section.*]

*[Editor’s note: In the context of Section 7.2.2, the difference between CCC and CPC should be clearly described. The expansion of CCC and CPC description and examples are needed. Text will be invited to the meeting.]*

This method entails a CRS node receiving a beacon signal by a source external to the CRS or a signal facilitating coexistence by a source external to or internal of the CRS. It can be applied to both coexistence scenarios.

One possibility is to use beacon signal broadcast at the location of a low-power or receive-only nodes of existing radio systems. If a CRS device receives such beacon signal, it shall not transmit to avoid causing harmful interference to the existing low-power or receive-only devices operating at the location or near of the CRS devices.

Another possibility is to use a control signal that provides information on frequency channels that are available at particular geographic location(s). Correspondingly, such control signal can be viewed as means to make available database information.

It is worth noting that the CPC could be also used as an enabler for providing the information contained in the database as described in the previous section, to cognitive radio system nodes.

There is also a possibility to use control signal exchanges between CRS nodes. CCC system control messages are exchanged containing the relevant spectrum usage information. This information only has to be shared with the relevant neighboring nodes, ensuring that the signaling load can be kept limited. Sharing the information between the involved CRS nodes ensures that the relevant nodes have the most accurate information of local available spectrum in a timely manner. The CRS may use the information to decide on a needed use of the spectrum. The CCC is a flexible concept that can operate over various topologies and network configurations.

### 7.2.3 Spectrum sensing

Spectrum sensing is one of the techniques contributing to obtaining knowledge by a CRS. More precisely, it provides information on spectrum occupancy [around the CRS node]. Spectrum sensing can be applied to both coexistence scenarios.

When CRS is looking for coexistence with other radio systems, spectrum sensing could provide timely indication of the existing radio system starting its operation. Also, spectrum sensing can assist in coexistence between CRSs.

### 7.2.4 Self-coexistence mechanisms

*[Editor’s note: The term “self-coexistence” should be re-worded since it may not be familiar with readers.]*

Some CRSs deploying a single RAT have the additional capability of being able to self-organize and use the spectrum amongst themselves.

Self-coexistence mechanisms in specific radio technologies (existing or being specified) are e.g.

*[Editor’s note: The following four items need to be examined at the next meeting. More explanatory text will be provided at the next meeting, e.g. more mechanism, accuracy for the current mechanisms and their parameters. The relationship of the following items with CRS should be clarified.]*

– TPC – transmit power control;

– FH – frequency hopping;

– Time-division multiplexing schemes and protocols;

– Message-based on-demand spectrum contention.

### 7.2.5 Cross-coexistence mechanism

*[Editor’s note: The term “cross-coexistence” should be re-worded since it may not be familiar with readers.]*

*[Editor’s note: more detailed technical description may be required to make the paragraph clear. The contribution is solicited whether this section should be deleted or retained with an improved text.]*

Some CRS deploying different RATs may have capabilities to share the spectrum, and operate simultaneously in the same part of the spectrum.

Cross-coexistence mechanisms in specific radio technologies (existing or being specified) typically rely on 3 key elements in any cross-coexistence mechanism:

– Neighbour discovery, which is the capability to discover other radio networks and nodes.

– Communication, which means the capability to communicate about spectrum needs and use among those radio networks and nodes.

– Spectrum use rules, covering established policies and commonly agreed rules, which guarantee non‑discriminatory access to the spectrum.

When put together these three elements establish a cross-coexistence etiquette. The scope of the IEEE 802.19.1 is to develop technology independent methods for coexistence among different or independently operated networks [for devices using TV white space.

### 7.2.6 [Flexible spectrum use (FSU)/Adjustment of spectrum between CRS networks based on Policies]

[Spectrum Sharing techniques such as Flexible Spectrum Use concept [1 [IST03]] are technical schemes that enable CRS networks to measure and exchange information between nodes within one or between different CRS networks such that the overall radio resources utilization could be optimized. The exchanged information would contain knowledge of spectrum utilization and certain system operating conditions e.g. load, traffic, interference, or dynamic/semi-dynamic agreement on spectrum usage, etc. With this knowledge nodes can dynamically take decision by a central or distributed decision making approach, on temporarily free spectrum/spatial resources to be used. Then, the node can adjust its radio spectrum resources, based on predefined polices [2 [BMM09]] [3[Ber05]] which take into account the particular conditions,

The adjustment of radio spectrum resources could be conducted with different granularity e.g. on band, carrier, channel, subcarrier level. This technical schemes could enable coexistence between systems [4[BKO09]] [5[HKL06]] as well as self-optimizing the capacity of systems according to the particular interference, traffic and load situation.]

### 7.2.7 [Relay transmission/Rerouting of the transmission]

*[Editor’s note: “relay transmission” may not be relevant to CRS. Clarification is required at the next meeting. More detailed technical description relevant to the CRS may be required to make the paragraph clear, i.e. how the relay transmission is relevant to CRS. The contribution is solicited whether this section should be deleted or retained with an improved text.]*

[Relay transmission is one method to exploit spatial degrees of freedom to make interference mitigated.

Relay could provide multiple paths for CRS’s transmission. Once the interference to existing radio systems occurs, CRS could reroute traffic through other paths. Moreover, with relay, the CRS’s transmission could be conducted with a lower transmit power and a shorter transmission range, so the interference to the existing radio systems could be reduced [45[Ch18]].

There are two modes of relay transmission which could be used in the CRS:

− dedicated relay transmission mode;

− dynamic relay transmission mode.

The dedicated relay transmission mode implies that a CRS device is configured as a dedicated relay station node.

The dynamic relay transmission mode implies that a CRS node could be selected as other cognitive device’s relay station temporarily to assist the relay transmission.

If supporting relay,CRS could firstly choose an appropriate path and secondly decide the corresponding relay station based on some analysis, e.g. the analysis on potential interference to existing radio systems.Also, the [radio resources for relay transmission need to be decided properly, e.g. including] spectrum resources, time-slots, power, etc. Finally, the CRS could inform the cognitive devices and the relay station node the transmission path and resource decision via control signalling.]

*[Editor’s notes: There are two views: one is that Section 8 should be deleted and any necessary material should be moved to any appropriate section(s) and other view is that this section should be retain with further modifications.]*

# [8 Technical consideration regarding the impact on spectrum use

There are two possible cases for deployment of CRS in the land mobile service, namely in bands where mobile service has an exclusive allocation or in bands with multiple allocations. Especially in the latter case the sharing and coexistence capabilities may become essential.

## 8.1 Sharing and coexistence considerations

Use of CRS technologies to facilitate co-existence of several systems could be useful as it may allow sharing in bands where it was not previously considered feasible and thus increase the efficiency of the overall spectrum use.Studies have shown that an essential issue is the protection of existing services from potential interference from the services implementing CRS technology, especially from the dynamic spectrum access capability of CRS. This situation can occur especially if the band is shared between an existing service and a service such as land mobile service employing CRS. Thus interference considerations are very important before CRS in land mobile service can enter the bands shared with other radiocommunication services.

Technical challenges may be especially related to applications which are receiving only, transmitting intermittently or the signal levels are very low. In those cases sensing may not provide sufficient protection. On the other hand the use of geo-location and databases may pose challenges with some applications where the deployment of stations is ubiquitous or registration of stations and their spectrum use in a database is otherwise difficult.

In addition, in order for CRS to operate and transmit without causing harmful interference, appropriate range of transmission parameters such as power levels and unwanted emissions should be made available.

Therefore, particular sets of CRS capabilities and technical characteristics may be needed to allow sharing or additional usage in bands shared with other radiocommunication services, depending on particular bands and applications.

In order to exploit the opportunities of CRS in the land mobile service to its fullest harmonized technical solutions could be beneficial. However, it should be noted that CRS is a technology that can be applied to the various systems for the various applications. Harmonised technical solutions would be useful to address possible CRS applications in various bands.

There may also be a need to utilize appropriate policies to facilitate sharing and coexistence, as discussed in Chapter 7.

## 8.2 Additional flexibility in spectrum use

As CRS will have the ability to dynamically and autonomously adjust their operational parameters and protocols it could facilitate new flexible operational approaches, e.g., to facilitate dynamic or temporal and spatial or geographical sharing requirements.

CRS can use spectrum flexibly over the time, but it can also avoid causing harmful interference to the primary service, even if that changes over the time. However, this ability depends on the particular application and band where certain radiocommunication services are involved and particular cognitive features such as sensing and access to database are required.

Use of sensing allows the CRS nodes to detect changes of the protected use around them and to act accordingly, based on the valid policy. The changes can usually be related to change of frequencies used by the primary service around the CRS nodes. But also technical changes of the signals to be detected may be handled as the sensing method may be sufficiently flexible or broad to cover   
a range of signals or technical changes in the signals of the protected services. More fundamental technical changes of the protected services, due to technology evolution and technology upgrades, can be handled through reconfiguration of the CRS nodes. It should be noticed, that also policy updates can be delivered to the CRS nodes.

Use of access to database by CRS nodes can ensure protection of primary services practically under any changes and evolution of the primary services. CRS nodes are following the updated orders from the database, where the changed protection requirements have been taken into account. Thus dealing with evolution of the primary services is more straightforward when the database approach is in use. The valid policies are implemented in this case by the database and the CRS nodes just continue to follow the orders, even if they are changed.]

# 9 Conclusion

[TBD]

Annex A

*[Part of Annex 9 to Doc. 5A/788]*

Radio technologies closely related to CRS

It is useful to understand the following technologies in terms of what they offer and the functionalities they provide: software defined radio (SDR), reconfigurable radio, policy based radio, smart antenna, dynamic frequency selection (DFS) and cognitive pilot channel (CPC).

*[Editor’s note: All sections should have explanatory text (including relevance to CRS) and not just references to external document.]*

# A.1 Software Defined Radio (SDR)

For SDR description, see Report ITU-R M.2117.

# A.2 Reconfigurable radio

Reconfigurable radios have the ability to update some or all of the physical layer signal processing and possibly higher layers of the protocol stack. The reconfiguration methods for a reconfigurable radio can vary significantly from physically changing out a line card, flashing a PROM (programmable read-only-memory), changing the image loaded onto an FPGA, or readdressing a pointer in memory. As an example, changing a card is a way in which the latest technology choices can be inserted into a radio network, and thereby continue to offer the latest in features and services at decreasing cost. As another example, it is common to be able to update the software of a remote base station by sending new software to it through a network connection, so in some cases reconfigurable radios may be updated very quickly, and in some cases, they may need to be powered down in order to be changed (offline vs. online update). A reconfigurable radio will share some of the benefits of an SDR (e.g. multimode, upgradeability, and reduced standards risk). However, when not implemented as an SDR, a reconfigurable radio typically exhibits longer reconfiguration times and less flexibility and control of transmission characteristics, which tends to make non-SDR reconfigurable radios a less attractive platform for cognitive radio. Numerous reconfigurable radios have been successfully fielded.

# A.3 Policy-based radio

Policy based radios can be updated in the field to adapt to local regulatory policy without a change to the internal software. While relatively new to the field of radio networks, internet routers have long been policy-based. In this way, the network operators have been able to use policy to control access privileges, allocate resources (bandwidth), and revise network topology and behaviour. It is a topic of discussion within regulatory organizations about how policy for radios will be defined and maintained, however, for cognitive radios, policy-based techniques enable products that can be used throughout the world, and automatically adapt to local regulatory requirements, and be updated as the regulatory rules evolve with time and experience. Experiments in policy-based radios have been performed in defence research, and test beds have been demonstrated, and the details on policy based radio control networks are now being analysed.

Policy-based radio could be one approach for achieving better spectrum utilization.

# A.4 Smart antennas

Information on smart antennas can be found in Report ITU-R M.2040.

# A.5 Dynamic frequency selection (DFS)

For DFS description, see Reports ITU-R M.2034 and ITU-R M.2115.

# A.6 Adaptive systems

For the description of adaptive systems, see Recommendations ITU-R F.1110 and ITU-R F.1611.

# A.7 Examples of implementations of the CPC

## A.7.1 Organization of geographical related information

There is a need to organize the information delivered over the CPC according to the geographical area where this information applies.

A difference can be made between two options differing on how they provide geographical related information:

− *Mesh-based approach:* The geographical area is divided into small regions, called meshes. In that case the CPC should provide network information for each one of these meshes, being possibly transmitted over a wide area and therefore including a lot of meshes. Initial requirements evaluations seem to conclude that this solution could require a very high amount of bandwidth.

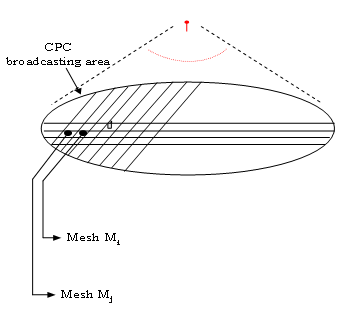
− *Coverage area approach:* In this approach, the coverage area is provided for the different RATs, thus the concept of mesh is not needed any more. For example, the following items could be provided in this approach: operator information, related RATs and for each RAT, corresponding coverage area and frequency band(s) information.

#### A.7.1.1 Mesh-based approach

The CPC operates in a certain geographical area that could be imagined as subdivided into meshes, as shown in Figure A7.1. A mesh is defined as a region where certain radio electrical commonalities can be identified (e.g. a certain frequency that is detected with power above a certain level in all the points of the mesh etc.). The mesh is uniquely defined by its geographic coordinates, and its adequate size would depend on the minimum spatial resolution where the above mentioned commonalities can be identified [38[Ch11]].

Figure A.7.1

Geographical area of the CPC divided into meshes



The coverage area of the heterogeneous networks could be divided into several meshes in geographical area. Each mesh can have different operational state, such as RATs, traffic load and etc. CPC could deliver information based on mesh-division. In the mesh division-based scenario, there are mainly three CPC information delivering approaches: broadcast CPC, on-demand CPC and multicast CPC mode.

The multicast CPC mode is an evolution of on-demand CPC delivery mode, which adopts point‑to‑multipoint information delivery approach. In this mode, the network should wait the requests of users from the same mesh for a period time before sending the request of this mesh into the scheduling system which would arrange the requests.

The multicast CPC utilizes the scheduling system to manage the information delivering. The multicast CPC functionality would send the information to the scheduling system first, and then the scheduling system would deliver the information to the terminals according to certain scheduling policies.

The out-band CPC-cells can be divided as meshes to improve the accuracy and efficience of the information delivered via CPC. And the mesh division scheme provide guidelines for how to divide meshes appropriately, in which the factors that are related to the mesh division size and have significant effects on the accuracy and efficiency of the information delivered via CPC should be considered, such as user density, information representation in multi-RATs overlapped meshes, dynamic mesh division size in multi-RATs overlapped scenario. Furthermore, the transmission delay of information delivery via CPC and the efficiency of overall procedure of CPC should also be considered.

### A.7.1.2 Coverage area approach

The CPC content for a given geographical area is organised considering the region, under-laying CPC umbrella, where such information has to be considered valid.

For instance, in case the CPC information is related to availability of operator/RAT/frequency the CPC information will be organised e.g. per coverage area of each RAT.

Knowing the position of the mobile terminal is not a strict requirement for the CPC operation using this approach, but a capability that enables higher efficiency in obtaining knowledge:

− in case positioning is not available, as long as the mobile terminal is able to receive the CPC information, the information about the different regions in that area are available;

− in case positioning is available, a subset of the information at the actual position could be identified. The mobile terminal could then use that information.

The structure of the basic CPC message to be conveyed in case of coverage area approach is reported in Figure A.7.2.

Figure A.7.2

CPC message structure



**RAT\_TYPE = GSM, UMTS, WiMAX, LTE…**

**COVERAGE\_EXTENSION = LOCAL/GLOBAL**

**FREQ\_LIST**

**COVERAGE\_AREA *(optional)***

**OPERATOR\_INFO**

**RAT\_LIST**

The structure of the CPC message includes the following fields:

− *Operator information*: operator identifier. This information is repeated for each operator to be advertised by the CPC.

− *RAT list*: for each operator, provide information on available RATs. This information is repeated for each RAT of *i*-th operator.

*• RAT type*: could be for instance “GSM”, “UMTS”, “CDMA2000”, “WiMAX”, “LTE”…

*• Coverage extension*: could be GLOBAL (i.e. wherever the CPC is received) or LOCAL (i.e. in an area smaller than CPC coverage).

*• Coverage area*: to be provided in case of LOCAL coverage (e.g. reference geographical point).

*• Frequency information*: provide the list of frequencies used by the RAT.

In the case of CPC Out-band solution, all the fields reported above are considered.

In the case of CPC In-band solution, other fields could be added to the reported ones. Such fields could include e.g. Policies, Context Information, etc.

## **A.7.2 Phased approach**

Figure A.7.3 presents the two main phases in the CPC operation taking into account the main steps of the overall CPC operation procedure described above and the availability of both out-band CPC and in-band CPC.

Figure A.7.3

CPC operation procedure

use of the **Outband CPC**

**Start-up information**

**Ongoing information**

use of the **Inband CPC**

Listen to out-band CPC in order to obtain basic parameters (e.g. available networks at that location)

Select and connect to a network using information from the out-band CPC; stop listening to the out-band CPC

Connect to the in-band CPC within the registered network

Listen to ongoing information using the in-band CPC

To broadcast data allowing a terminal to select a network in an environment where several technologies, possibly provided by several operators, are available

e.g. much more detailed context information, policies for reconfiguration management

## **A.7.3 Out-band and in-band characteristics**

The characteristics of out-band and in-band parts of the CPC are summarized in the following Table 1.

Table A.7.1

Characteristics of out-band and in-band parts of the CPC

|  |  |  |
| --- | --- | --- |
| Characteristics | Outband CPC | Inband CPC |
| Information conveyed | Start-up information, e.g. context information on available networks at that location | Ongoing information, e.g. much more detailed context information, policies for reconfiguration management, etc. |
| Channel bit rate requirements | Initial requirements evaluations seem to conclude that relatively low bit rate is required in case of coverage area approach, while mesh-based approach could require a very high amount of bandwidth. | |
| Data direction | Downlink. Optionally uplink | Downlink and Uplink |
| Bearer | Most likely a harmonized frequency band, wide-area coverage. Might be a novel RAT, or a legacy technology of appropriate characteristics (e.g. GSM channel) | A bearer in a operator’s network (e.g. a logical channel mapped on a UMTS bearer) |

# [A.8 An Example of CRS Deployment based on SOR]

[Figure A8.1 illustrates an example of CRS deployment based on SOR. A CRS is composed of Operator A, Operator B and a service provider. Operators and service providers provide various function modules in service manner, modulation/demodulation services, audio encoding/decoding services, reasoning services. These services are deployed distributedly in the network.

According to user requirements and wireless environment, Operator B uses the sensing service provided by Operator A, the spectrum analysing service and reasoning service provided by service provider to implement spectrum sensing and analysing function and decision making function. According to the decision results, Operator B orchestrates modulation/demodulation services, audio encoding/decoding services, video encoding/decoding services, etc., to form an appropriate waveform to meet the user requirements. Thus CRS reconfiguration is completed.

Figure A8.1

CRS deployment based on SOR



With this method, it is unnecessary for operators to deploy all functions within each base station. Partial functions can be processed by third parties through customized services thus saving construction costs, increasing efficiency, improving scalability, facilitating the development of new business.

]Annex B

*[Part of Annex 9 to Doc. 5A/788]*

Relationship between SDR and CRS

# B.1 Conceptional Relationship between SDR and CRS

Software defined radio is recognized as an enabling technology for the cognitive radio system. SDR does not require characteristics of CRS for operation. One can be deployed/implemented without the other.

In addition, SDR and CRS are at different phases of development, i.e., radiocommunication systems using applications of SDR have been already utilized and CRS are now being researched and applications are under study and trial.

Furthermore, SDR and CRS are not radiocommunication services but are technologies that can be implemented in systems of any radiocommunication service. Moreover, it is seen that SDR and CRS are two technologies which can be combined.

From the viewpoint of the progression in the development of the Software Defined Radio (SDR), the signal processing technology has played major role, because it enhanced the digitalization of the communication equipment. Therefore, several kinds of signal processing become to be possible, which are not attainable by the analogue devices. At the initial stage of the SDR development, analogue devices are replaced to signal processor and A/D and D/A converters. Then, signal processing can be controlled by the CPU (Central Processing Unit) with intelligence. Considering these development steps, the SDR may be the basis of the CRS, although it is also said that the SDR and CRS are not dependent with each other. The SDR is one of the tools for realization of the reconfiguration functions.

One example of conceptual relationship is depicted in Figure B.1. The SDR is the composite entity of the hardware, software and processing capability, which provide the capability of adjustment for the CRS to achieve the predefined objectives. For such objectives the cognitive radio system (CRS) will obtain knowledge regarding the operational and geographical environment, learn from the results obtained, and furthermore adjust its operational parameters and protocols, e.g. modulation scheme.

Figure B.1

Example of conceptual relationship between cognitive radio system (CRS)  
and software defined radio (SDR)

Processor (CPU + memory, et al.)

hardware and software (reconfigurable device, et al.)

CRS

(function)

SDR

(entity)

predefined objectives of radiocommunication system

SDR provides a capability of “adjustment”

*[Editor’s note: The arrow in Figure B.1 should be bi-directional. Modification is required at the next meeting.]*

Annex C

*[Part of Annex 9 to Doc. 5A/788]*

Frequency Time Sharing (FTS)

*[Editor’s note: Text should be updated focusing on only technical approach. The relevance to CRS should be described. The difference from a conventional database approach should be described.]*

# [C.1 Principle of frequency time sharing

In those cases where it is known at forehand for how long temporary unused spectrum can be made available for CRS-use, [those frequencies may be made available to a Cognitive Radio database] including sharing time which labels the time in minutes to months. And before the sharing time ends the party offering this temporary available frequency may decide to prolong the sharing time for another period.

In effect a temporary available frequency can in this way be made available in sequences of time slots over a long period.

# C.2 Capacity

Mobile equipment like smart phones needs much more capacity than speech only applications.

Temporary available frequencies used by Cognitive Radio Systems may not be the most optimal choice for speech applications, because availability cannot always be guaranteed.

# C.3 Protocol for lease time

Within the internet protocol the principle of lease time is used for issuing temporary IP addresses. A comparable principle can be used for offering temporary available frequencies. Such protocols including lease time is also described in draft ETSI TS 102 800 on “Cognitive Programme Making and Special Events C-PMSE: Protocols for spectrum access and sound quality control systems using cognitive interference mitigation techniques.” [The protocol within ETSI TS 102 800 also mentions the possibility of Machine-to-Machine (M2M) trading of spectrum.]

Figure 1

Fixed mobile control channels

Used FSS channels

Future FSS use

use

Dynamically available

Mobile traffic channels

]

Annex D

*[Part of Annex 9 to Doc. 5A/788]*

An example of higher utilization due spectrum pooling  
enabled by cognitive radio

*[Editor’s note: Additional text which refers to Scenario 6.2 in CRS1 report should be added.]*

# D.1 Discussion

An operator today must manage a heterogenic radio environment due to its multiple services, different network architectures, various multiple access techniques and multiple frequency bands. Intra-operator spectrum pooling enabled by cognitive radio is becoming essential in order to balance the load of the different networks that represent different technologies and different generations. Spectrum pooling also can increase the utilization of the scarce resources available.

The continuing growth of mobile radio systems is driving demand for more efficient use of spectrum. Spectrum pooling is a novel approach to radio resource management enabled by cognitive radio. A simple example to show the benefits of spectrum pooling enabled by cognitive radio is shown below.

# D.2 Example of higher utilization due spectrum pooling enabled by cognitive radio

In this calculation the resource needed for each call is assumed to be one channel. It is assumed that there are two different groups of spectrums available. Each spectrum group has 18 channels. It is also assumed that the performance criterion is not to exceed 1% probability of blocking.

## D.2.1 Scenario 1

Two groups of spectrum that are completely partitioned. Each spectrum group is assumed to support 10 identical calls at 1% probability of blocking

|  |  |  |  |
| --- | --- | --- | --- |
| Spectrum are not shared: each group is fully utilized | | | Spectrum are pooled |
| Group 1 | Group 2 | Group 1 + Group 2 | Group 1 + Group 2 |
| 10 calls | 10 calls | 20 calls | 25 calls |
| 18 channels | 18 channels | 36 channels | 36 channels |
| Utilization = 55% | Utilization= 55% | Utilization = 55% | Utilization = 69% |

## D.2.2 Scenario 2

Two groups of spectrum that are completely partitioned. It is assumed that the first group is not fully utilized, where the number of calls serviced is = 2 calls; and group 2 is overloaded (more that 10 calls) which resulted in unacceptable probability of blocking (higher than 1%)

Each group is assumed to support 10 identical calls at 1% probability of blocking.

|  |  |  |  |
| --- | --- | --- | --- |
| Resources are not shared: group 1 is not fully utilized | | | Resources are pooled |
| Group 1 | Group 2 | Group 1 + Group 2 | Group 1 + Group 2 |
| 2 calls | 10 calls | 12 calls | Can support up to 25 calls (2 calls from group 1 and 23 calls from the overloaded group 2) |
| 18 channels | 18 channels | 36 channels | 36 channels |
| Utilization = 11% | Utilization = 55% | Utilization = 33% | Utilization = 69% |

1. <http://www.crowncom2010.org/keynote.shtml> [↑](#footnote-ref-1)
2. Initial camping identifies the procedure followed by a terminal at the start-up in order to select an appropriate network cell. [↑](#footnote-ref-2)
3. In this case, there is no core band for the network operation. [↑](#footnote-ref-3)
4. There is standardization effort by Internet Engineering Task Force (IETF) to standardize a Protocol to Access White Space databases (PAWS). [↑](#footnote-ref-4)
5. James Neel, R. Michael Buehrer, Jeffrey Reed, Robert P. Gilles, Game theoretic analysis of a network of cognitive radios, Virginia Tech, Blacksburg, Virginia 24061 USA.   
   http://ieeexplore.ieee.org/iel5/8452/26621/01187060.pdf?isnumber=26621&prod=CNF&arnumber=1187060&arSt=+III-409&ared=+III-412+vol.3&arAuthor=Neel%2C+J.%3B+  
   Buehrer%2C+R.M.%3B+Reed%2C+B.H.%3B+Gilles%2C+R.P [↑](#footnote-ref-5)